# Report on Emerging and Converging Technologies

## CHPM2030 Deliverable D6.1

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CHPM2030

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# CHPM2030 DELIVERABLE D6.1

# Report on Emerging and Converging technologies

This report summarises the methodology and results of the three foresight tools (Horizon Scanning, Delphi survey, Visioning process) deployed during the CHPM2030 foresight exercise, outlines future emerging and converging technologies that can help the realization of the CHPM scheme, and ultimately, it presents a vision, an ambitious future state that will be used by the upcoming CHPM roadmap 2030 and 2050.

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## LIST OF ABBREVIATIONS

*AI: Artificial Intelligence*
*CEC: Chemical Energy Carriers*
*CRIRSCO: Committee for Mineral Reserves International Reporting Standards*
*DTH hammer: down-the-hole hammer drilling technique*
*Dx.y: Deliverable x=Work Package, y= number of deliverable in the WP*
*EC: European Commission*
*EFG: European Federation of Geologists*
*EGEC: European Geothermal Energy Council*
*EGS: Enhanced/Engineered Geothermal System*
*ETIP: European Technology & Innovation Platform on Deep Geothermal*
*EU: European Union*
*GIS: Geographic Information System*

*H&S: Health and Safety*
*HS: Horizon Scanning*
*IGA: International Geothermal Association*
*IRENA: International Renewable Energy Agency*
*LPRC: La Palma Research Centre*
*LTP: Linked Third Parties*
*ML: Machine Learning*
*NIMBY: Not In My BackYard*
*O&G: Oil & Gas*
*PR: Public Relations*
*REE: Rare Earth Elements*
*RMI: EC's Raw Materials Initiative {SEC(2008) 2741}*
*ROI: Return of Investment*
*SET Plan: Towards an Integrated Strategic Energy Technology Plan: Accelerating the European Energy System Transformation (C(2015)6317)*
*SLO: Social Licence to Operate*
*SMART goals: Specific, Measurable, Attainable, Realistic and Time-based goals*
*TRL: Technology Readiness Level*
*UNFC: United Nations Framework Classification for Resources*
*UNIM: University of Miskolc*
*VITO: Flemish Institute for Technological Research*
*WP: Work Package*

## 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

There are many innovative geothermal or mineral projects in the EU, but CHPM2030 is unique for tackling both mineral raw material dependency and sustainable energy supply of the EU, under a single interlinked process.

The Combined Heat, Power and Metal extraction (CHPM), geothermal technology being developed by the CHPM2030 project Consortium, is currently at a relatively low Technology Readiness Level (TRL): from 3 to 5, depending on the component. The concepts that have been developed within the framework of this project aim to increase the economics of deep geothermal projects (especially EGS) by extracting valuable metals from the geothermal brine. The first pilots (TRL 6-7) are envisioned by 2030 and the full-scale applications (TRL 8-9) by 2050. Commercial implementation targets are thus years and decades beyond the duration of the CHPM2030 project. The aim of the future-oriented strategic planning process described in this study is to ensure that the targets can be achieved by 2030/2050 or sooner.

The Roadmapping and Preparation for Pilots Work Package (WP6) utilises the synergetic combination of foresight methods (Deliverable 6.1) and evaluates study areas (Deliverable 6.2) in order to deliver a roadmap, a strategic plan, an agenda for 2030 and 2050 (Deliverable 6.3), that leads to the desired end-state of the CHPM technology.

This report summarises the methodology and results of the three foresight tools (Horizon Scanning, Delphi survey, Visioning process), outlines future emerging and converging technologies that can help the realization of the CHPM scheme, and ultimately, it presents a Vision, an ambitious future state that the roadmap can reach for.

The Horizon Scanning exercise gathered relevant factors, trends, drivers of change, and outlined the present technological baseline, as an orientation for the Delphi survey. It used an Expert workshop for mapping key interest areas, gap analysis and statement formulation. The emerging topics were related to geothermal drilling, EGS reservoir management, metal recovery, financing, energy conversion, production technologies, well control and monitoring, developments in material science, deep metal enrichment and exploration, data protocols, geophysical methods, structural geological framework, data processing with Artificial

Intelligence (AI) and Machine Learning (ML), socio-economic aspects, political-, social-, and environmental background.

The Delphi survey is an Expert input based, iterative process that can help to generate consensus about relevant technological developments. The outcomes of the Horizon Scanning exercise were converted into 12 Delphi statements. The time horizon was set to 2050, and the statements encouraged free commenting on the following topics: drilling risk, reservoir stimulation, metal mobilization, geochemical processes, corrosion, geophysics, data processing, investors, drilling depth, public acceptance, revenue streams and market penetration. The survey was sent in two rounds to both geothermal and mineral groups, mobilising expertise from both research communities. 133 Experts participated word-wide. The outcome of the survey is the further definition (agreement, realization time horizon, emerging issues, etc.) of the previously identified topics, for the visioning exercise.

The Vision is an idealized future state: it defines “where to go” and what needs to be achieved within the investigated areas, in order to reach pilot/commercial scale readiness level. The previous topics were grouped to 4 overarching themes: exploration, development, operation, market. The process used the outcomes of the Horizon Scanning, Delphi survey and a Visioning workshop to set “SMART” goals (specific, measurable, attainable, realistic, time-based) for each subtopic. At the workshop the participants defined preferred goals for 2030 and 2050, that would be required to enable the technology implementation by 2030 and 2050. The sum of the targets is the vision, that describes the desired destination in the future. The result is the description of what is envisioned at each theme with tangible targets for 2030 and 2050.

There has been a wide range of emerging issues and technologies identified during the Horizon Scanning, the Delphi survey and the Visioning process, that show strong convergence towards the successful implementation of the CHPM technology. The investigated topics were further developed and refined during the process through Expert input from both the geothermal and mineral communities. The outcome is a set of issues and goals to be tackled during the upcoming research/demonstration projects. The implementation framework (i.e. a Roadmap for 2030 and 2050) for the CHPM targets is contained in the final deliverable of WP6 (D6.3).

## 2. Introduction

Work Package 6 Roadmapping and Preparation for Pilots aims to set the ground for a pilot implementation of the proposed technology, bearing in mind that CHPM2030 is a low-TRL research project, based on a novel idea that needs further nurturing and support beyond the immediate duration of the project. In order to support this goal, a technology roadmap was created that outlines the desired vision in the future and the actions and steps needed to take to arrive to this vision (pilot and commercial readiness level by 2030 and 2050 respectively), which is the main outcome of the work package. In order to deliver this roadmap document, several other steps needed to be taken along Task 6.1 and Task 6.2 (Figure 1).

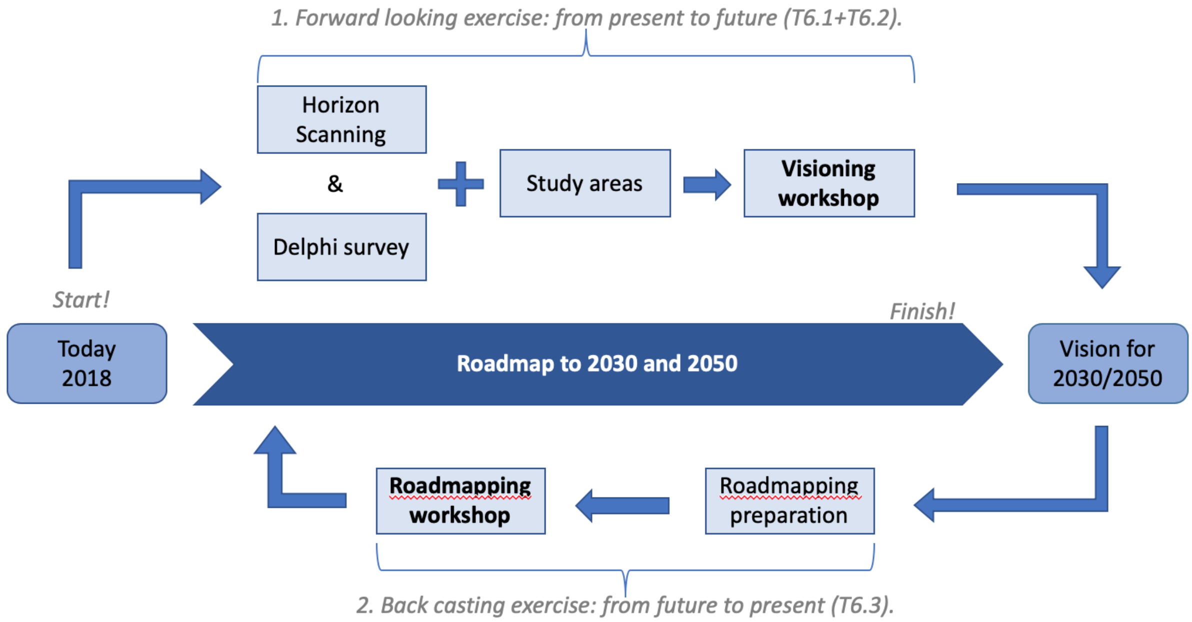



*Figure 1: WP6 Roadmapping and Preparation for Pilots workflow*

This forward looking exercise started from the present technological baseline towards the future, with the help of Horizon Scanning, Delphi survey and a Visioning process. Horizon Scanning provided the present technological baseline, with an expert workshop on mapping key interest areas and gap analysis. The results were formulated into Delphi statements covering various aspects of the technology. The 2-round Delphi provided more pieces of the puzzle of what the future may look like concerning key interest areas. The next step was the Visioning workshop. The participants picked up key topics identified through Horizon Scanning (HS) and the Delphi survey were explored to define preferred targets for two time frames to enable the technology implementation at TRL 6-7[1] by 2030, and TRL 8-9[2] by 2050. The sum of the targets is the Vision that describes what is the desired destination in the future. This line of activities includes the Task 6.2, investigating 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. These results are summarised in the *Deliverable 6.2 Report on Pilots* document.

The second line of activities started with the desired vision in the future, and used a roadmapping workshop and backcasting exercise to identify, what actions need to be taken in the present in order to arrive to the desired future destination (Vision), with the pre-assessed study areas and CHPM prospective locations, identified by EFG's Linked Third Parties, through emerging issues (Delphi) from the technology baseline of today (HS). The Roadmap document is building on Deliverable 6.1 and 6.2

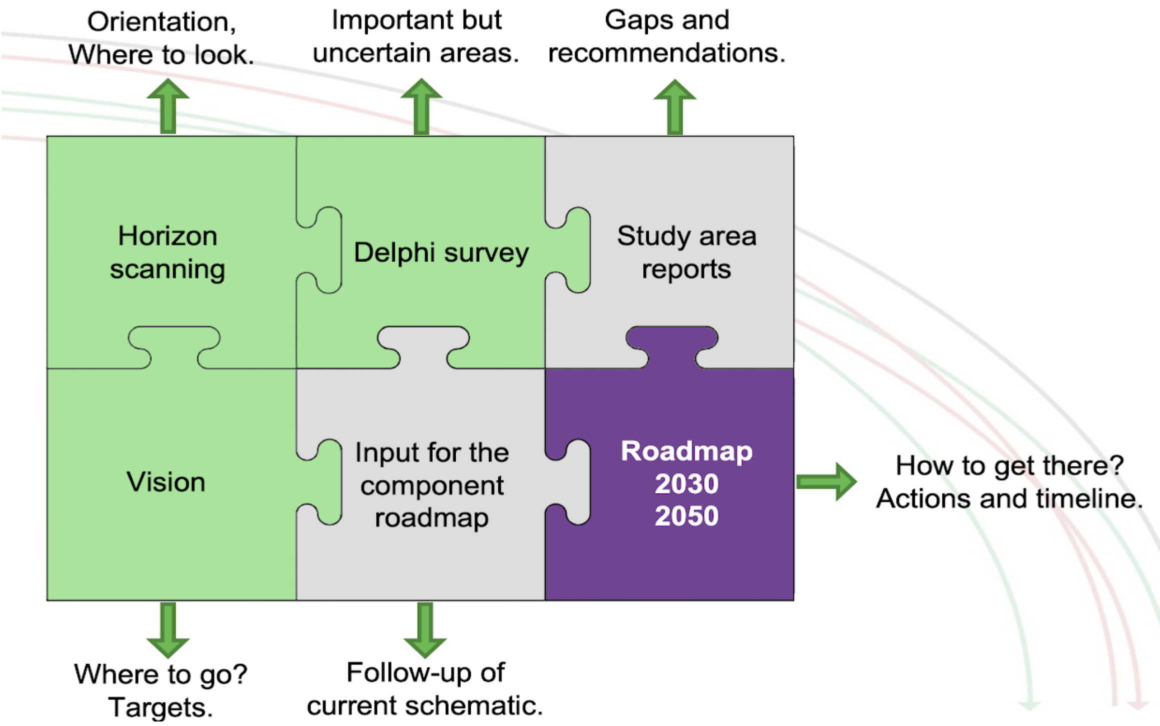



*Figure 2: Connection of different elements in WP6*

[1] TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies); TRL 7 – system prototype demonstration in operational environment

[2] TRL 8 – system complete and qualified; TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Therefore, in WP6, the first two main lines of activities were the preparation and implementation of the 2-round CHPM2030 Delphi survey in Task 6.1; and the formulation of an CHPM area evaluation template and framework to investigate study areas and to select and evaluate European areas for CHPM potential, with parallel development at each study areas in Task 6.2.

Task 6.1 represents the long-term planning component of the project, and it includes different foresight elements. Horizon Scanning (HS) provides the present technological baseline for CHPM today which will serve as orientation, the Delphi survey informs on important but uncertain future areas, and the Vision describes the desired destination with targets, in the future for CHPM technology (Figure 2).

## 3. Review of past studies and projects

As CHPM is a low-TRL technology concept, it needs further nurturing and future oriented thinking. Besides CHPM2030, there are many other projects and initiatives that research the future of either the geothermal or the mineral sector. During the development of Task 6.1, especially during the Horizon Scanning, Visioning and Roadmapping workshops these different sources of information were used, for orientation, framing and to stimulate discussion. This activity was also part of the Horizon Scanning efforts. These relevant sources of information are shortly summarised in this chapter, providing different "pieces of the puzzle".

It is also important to look out for running geothermal and mineral projects that may provide results for the future of CHPM technology. Below is a short inventory of running Geothermal projects, inserted from geothermalresearch.eu website.

*DEEPEGS: DEPLOYMENT OF DEEP ENHANCED GEOTHERMAL SYSTEMS FOR SUSTAINABLE ENERGY BUSINESS - The goal with the DEEPEGS project is to demonstrate the feasibility of enhanced geothermal systems (EGS) for delivering energy from renewable resources in Europe.*

*DESTRESS: Demonstration of soft stimulation treatments of geothermal reservoirs - DESTRESS demonstrates methods of enhanced geothermal systems (EGS). The aim is to* *expand knowledge and to provide solutions for a more economical, sustainable and environmentally responsible exploitation of underground heat.*

*GEMex: Geothermal Cooperation Europe Mexico for EGS and super-hot geothermal systems. The joint effort is based on three pillars: 1. Resource assessment at two unconventional geothermal sites. 2. Reservoir characterization using techniques and approaches developed at conventional geothermal sites. 3. Concepts for site development.*

*GEORISK: Developing geothermal and renewable energy projects by mitigating their risks. The GEORISK project will work to establish risk insurance all over Europe and in some key target third countries to cover the exploration phase and the first drilling (test). It means activities to be funded before financial institutions and IPP funding the confirmation drilling and surface systems.*

*GEOENVI: Tackling the environmental concerns for deploying geothermal energy in Europe. The objective of GEOENVI project is to make sure that deep geothermal energy can play its role in Europe's future energy supply in an increasingly sustainable way and to create a robust strategy to answer environmental concerns.*

*GEOTHERMICA: The main objective is to combine the financial resources and know-how of 16 geothermal energy research and innovation programme owners and managers from 13 countries and their regions.*

*GeoWell: Innovative materials and designs for long-life high-temperature geothermal wells. The GeoWell project will address the major bottlenecks like high investment and maintenance costs by developing innovative materials and designs that are superior to the state of the art concepts*

*MEET: Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials - The project addresses the need to capitalise on the exploitation of the widest range of fluid temperature in enhanced geothermal systems (EGS) plants and abandoned oil wells. The project's objective is to boost the market penetration of geothermal power in Europe.*

*SURE: Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource - Within the EC funded Horizon 2020 project SURE the radial water jet drilling (RJD) technology will be investigated and tested as a method to increase inflow into insufficiently producing geothermal wells.*

*ThermoDrill: Fast track innovative drilling system for deep geothermal challenges in Europe. The unique feature of the new concept is that penetration is achieved by a high pressure fluid jet which supports conventional rotary drilling by breaking the stress in front of the bit to increase bit performance.*

This is not an exhaustive list, there are many large scale geothermal research projects, such as Utah FORGE in the USA. On the other hand, the mineral industry is also busy with innovative projects, supporting the implementation of the EC's Raw Materials Initiative (RMI 2008), which identified three pillars of the EU access to raw materials:

1. Fair and sustainable supply of raw materials from global markets
2. Sustainable supply of raw materials within the EU
3. Resource efficiency and supply of "secondary raw materials" through recycling

Some of the examples of the running projects, supporting different pillars of the EU access to raw materials are listed here.

*The UNEXMIN project is developing a novel robotic system formed by three individual robots for the autonomous exploration and mapping of Europe's flooded underground mines. The Robotic Explorer (UX-1) will use non-invasive methods for autonomous 3D mine-mapping to gather valuable geological and mineralogical information.*

*The ¡VAMOS! project has designed and built a robotic, underwater mining prototype with associated launch and recovery equipment. The system is being tested on various sites in Europe.*

*The INTRAW project was formulated with the objective of mapping best practices and boosting cooperation opportunities on raw materials with technologically advanced non-EU countries (Australia, Canada, Japan, South Africa, & US) in response to similar global challenges. The ultimate result is the International Observatory for Raw Materials as a definitive raw materials knowledge management infrastructure.*

*The ProMine Project (Nano-particle products from new mineral resources in Europe) was a large, EU funded project, dealing with Resource Assessment, New Products and Sustainability Assessment and Exploitation. All potential metallic and non-metallic mineral resources (known and predicted) within the EU was documented in the first ever pan-European GIS based resources and modelling system. Detailed 4D computer models were produced for* *four metalliferous regions in Europe. In addition, life cycle cost analysis and environmental sustainability of the new materials were performed.*

EURARE *'Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits', was another project supporting the mineral raw material supply of the EU. The main goal of the EURARE project was to set the basis for the development of a European REE industry that will safeguard the uninterrupted supply of REE raw materials and products crucial for the EU economy industrial sectors, such as automotive, electronics, machinery and chemicals, in a sustainable, economically viable and environmentally friendly way.*

Minerals4EU *project is designed to meet the recommendations of the Raw Materials Initiative and will develop an EU Mineral intelligence network structure delivering a web portal, a European Minerals Yearbook and foresight studies.*

MINATURA2020*, EU funded project was advancing the concept and methodology for the definition and subsequent protection of "mineral deposits of public importance" to ensure their "best use" in the future in order to be included in a harmonised European regulatory/guidance/policy framework.*

*The* $I^2$Mine *(Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future) project marks the start of a series of activities designed to realise the concept of an invisible, zero-impact mine. The* $I^2$*Mine project will develop the innovative methods, technologies, machines and equipment necessary for the efficient exploitation of minerals and disposal of waste, all of which will be carried out underground.*

Regarding the future of these sectors, geothermal and mineral, there are many publications available with different time horizons. However, these are never about predicting the future, but instead explore different future pathways, plausible, probable and preferable scenarios, and creating a shared vision we can aim for.

The European Geothermal Energy Council (EGEC) published a Vision for Deep Geothermal[3]. They describe the state of geothermal energy today, new technologies for future geothermal development with 2050 timeline and the City of the Future. *City of the future and its attributes (100% renewable power sources in terms of electricity, heating/cooling and mobility, with zero impact on the environment (no pollution, no GHG emission, no long distance transportation*

[3] https://www.etip-dg.eu/front/wp-content/uploads/ETIP-DG_Vision_web.pdf

*of fossil fuels), where citizens will act as "prosumers" in a smart, clean, renewable and sustainable system.).* It is also envisioned that a large part of domestic heat and electrical power in Europe is coming from geothermal energy.

The Strategic Energy Technology (SET) Plan[4] is the "Declaration of intent on Strategic Targets in the context of an Initiative for Global Leadership in Deep Geothermal Energy" from the European Commission. Geothermal is a key technology in this vision. By 2050, it is expected that large geothermal power plants can be developed in ultra-hot reservoirs, which would supply large part of Europe' baseload electricity. This document also sets strategic targets in Deep Geothermal energy:

1. Increase reservoir performance resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030;
2. Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050;
3. Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025;
4. Reduce the exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015;
5. Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015;
6. Demonstrate the technical and economic feasibility of responding to commands from a grid operator, at any time, to increase or decrease output ramp up and down from 60% - 110% of nominal power.

The European Technology & Innovation Platform on Deep Geothermal (ETIP) is an EC endorsed, open stakeholder group under the Strategic Energy Technology Plan (SET-Plan), with the overarching objective to enable deep geothermal technology to proliferate and reach its full potential everywhere in Europe. Currently the Strategic Research and Innovation

[4] https://setis.ec.europa.eu/system/files/integrated_set-plan/declaration_of_intent_geoth_0.pdf

Agenda[5] is being prepared. This document recommends actions addressing the following key challenges:

- Technological challenges: 1) Prediction and assessment of geothermal resources, 2) Resource access and development, 3) Heat and electricity generation and system integration
- Transversal challenges: 4) From R&I to deployment (environmental, regulatory, market, policy, social, human deployments), 5) Knowledge sharing (data harmonization and coordinated organization of data and information, shared research infrastructures)

The European Technology Platform on Renewable Heating and Cooling presents a short-term roadmap: Geothermal Technology Roadmap (RHC-Platform, 2014). The document focuses on the state of the art and 2020 objectives, key performance indicators, implementation plan for 2013-2020 and potential solutions for future financing.

The research on geothermal energy is a hot topic outside of Europe too. The Massachusetts Institute of Technology (USA) published *The Future of Geothermal Energy - Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century (MIT, 2006)*. This document presents many aspects from the resource base assessment, drilling technologies, EGS reservoir stimulation, energy conversion technologies, environmental aspects and economic feasibility issues. Few years later the Stanford University published *A Technology Roadmap for Strategic Development of Enhanced Geothermal Systems (Ziagos et al, 2013).* The report characterized technology evolution timelines with 5 years intervals for each *Characterise, Create and Operate* EGS research topics.

In 2011 the International Energy Agency published the *Technology Roadmap Geothermal Heat and Power (IEA, 2011).* After outlining the geothermal energy today, the authors describe a Vision for deployment of geothermal energy (based on the *ETP 2010 BLUE Map Hi-REN* scenario) in which geothermal is a contributor to the CO2 reduction efforts. The roadmap recommends action, milestones and related stakeholders. Important issues have been addressed, such as public geothermal information systems, geothermal heat use, advanced

[5] http://www.etip-dg.eu/front/wp-content/uploads/ETIP-DG_SRA_public_consultation.pdf

EGS applications, drilling technologies and downhole instrumentation, regulatory framework and support incentives, market facilitation and transformation, funding, international cooperation, etc.

The *Megatrends in the global energy* (Rosenkranz, 2015) transition is a publication dealing with the global conversion of the energy system, towards a low-risk energy system, and argues that the end of the fossil-nuclear era has already begun. The report identifies five megatrends on a global scale: *1. The end of the fossil era has begun, 2. The energy future has already begun, 3. The energy future is renewable, 4. The energy future is decentralised, 5. The energy future is digital*.

Turning towards the forward looking studies of the mineral sector, the Mining & Metals in a Sustainable World 2050 (WEF, 2015) provides interesting insights about the mining and metals industry. The authors present a framework that connects future drivers of change, themes of transition, scenarios on the future resources, and Roadmap/actions. Three scenarios are also presented: *A world of two speeds, Resource abundance, Global fragmentation*. Each scenario is addressed with a short overall *Roadmap for the mining and metals community*, and *Specific actions for the mining and metals community (Mining and Metal companies, Governments, Local community and civil society, Investors)*

In 2017 Australia, as a technologically advanced country in the mining sector, presented the *Mining Equipment, Technology and Services A Roadmap for unlocking future growth opportunities for Australia (CSIRO, 2017).* Beside describing global mining megatrends, the report identified areas for growth. These identified areas, relating to 2-3 megatrends are Data driven mining decisions, Social and environmental sustainability, Exploration under cover, Advanced extraction, Mining automation and robotics. There are areas that are important not only for Australia, but for Europe too.

When it comes to overall vision, in 2012 the European Commission published Global Europe 2050 (EC, 2012). The report first characterizes current unfolding issues and trends. Experts alternative future pathways, where the EU may be by 2050, together with wildcards of the different dimensions of the 3 scenarios:

- Further European integration - 'EU Renaissance': political, fiscal and military integration, high GDP growth, efficient innovation system, strong economic and social development,
- Fragmented European Integration - 'EU Under threat': protectionist measures, GDP decline, food and oil crises,
- Standstill in European Integration - 'Nobody cares': the EU only muddles along with no clear vision or direction, low economic growth,

The Energy Roadmap 2050 (EC, 2012), communicated by the European Commission in 2012 assesses the challenge of reaching a secure, competitive and decarbonised energy system by 2050. The report presents challenges and opportunities along the way from 2020 to 2050. The areas covering the need to 1) transform the current energy system, 2) rethink the energy markets, 3) mobilise investors, 4) engage the public, 5) drive the change at the international level. Geothermal is included in the renewable energy technologies.

There are many overlapping emerging issues already identified in these reports and projects, that are relevant in the future of geothermal and mineral sectors. These future trends and emerging technologies related to novel exploration, risk mitigation, reservoir stimulation, drilling techniques, international cooperation, big data, innovative mining techniques, etc. helped framing the development of forwards looking efforts in WP6.

## 4. Horizon Scanning

After the scene was set by the review of past studies, projects and literature, as illustrated in the previous chapter, a small-scale Horizon Scanning (HS) exercise was conducted in order to identify and separate relevant factors, drivers of change, trends and issues, and ultimately to define important but uncertain areas that may shape the future of CHPM technology. This work included the organisation of an Experts workshop in Lanzarote, Spain.

Horizon scanning or environmental scanning serves as an early warning system to identify potential threats and opportunities (Bengston, 2013). In other words, HS is a systematic outlook to detect early signals, trends, wilds cards, 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).

The first WP6 workshop was dedicated to a Horizon Scanning exercise, which was organised together with the CHPM2030 consortium meeting in 21-23 March 2018. Since this exercise prepared the way for the upcoming Delphi survey, during the introduction, both Horizon Scanning and Delphi methodology way presented. Both these foresight tools had the objective to obtain experts' opinions on the critical interest areas in CHPM technology. First, the structure and topics were drafted by LPRC and it was refined/completed during the workshop group work with the input from all Consortium partners. During this workshop, 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, such as geothermal drilling, scaling, metal recovery, exploration, etc.
2. **Gap analysis** to investigate what are the bottlenecks, difficulties, challenges, enablers within a given key interest areas.
3. **Statement formulation** to generate concrete ideas for topics in the Delphi survey.

*Figure 3: Discussions at the Lanzarote workshop (21-23.03.2018.)*

The work has been split into two groups and was facilitated by moderators from LPRC (Figure 3). Group results were then presented by the moderators, highlighting challenging issues that: 1) require solutions beyond the lifetime of the project, and 2) require further discussions and elaboration with the help of the project's Expert community. During this stage both sector-specific issues (mineral + geothermal) and overall issues were identified.

Regarding the geothermal sector, the following key interest areas were identified, including subtopics and gaps:

- Geothermal drilling: exploration risk, drilling risk (yield of the well, permeability, drilling insurance, offshore operations), safety (high pressure reservoirs, incidents).

- EGS reservoir management: geochemical dynamics, resource assessment (geothermal recovery factor, metal recovery factor, reuse of exhausted reservoirs), communication between injection and production wells, selective leaching, reservoir stimulation, communication between industry and academics.
- Metal recovery: access to truly relevant metal containing brines, new strategies to increase selectivity, conceptual models for scaling up reactor design from lab to pilots, technology transfer from research to industry, element specific removal of interest metals at low concentration brines, alternative value chains (CO2 storage, CO2 working fluid), time factor of metal leaching.
- Financial aspects: drilling insurance, competition with other energy sources (cheap solar, hydro, wind, biomass), investors interest, stockpiling.
- Energy conversion: additional electrochemical/chemical power generation, harmonization of each CHPM technological building blocks.
- Production technologies: proppants, downhole pumps, scaling and corrosion, gases, Eh/pH conditions.
- Well control and monitoring: advanced sensor development (electrochemical, optical, piezoelectric) resisting to high pressure/temperature.
- Material development: corrosion (cost, manufacturing), material selection.

Regarding the mineral sector, the following key interest areas were identified, including subtopics and gaps:

- Deep metal enrichments and exploration: Focus on known mineralized/resources – extensions, low grade large tonnage, good understanding of hydrothermal alteration halo (diffuse metal distribution, understand zonation, properties, geometry, nature etc.). Regional extensional zones can also be potential areas. Usually elevated heat flow and multiple mineralization phases/overlapping.
- Develop data protocols – collaboration between industry and research institutions.
- Geophysical methods: improvements on resolution.
- Structural geological framework: 4D models, flow circulation model, hydrogeological model (fluid flow model) – flow rate, direction.
- Machine Learning, Artificial Intelligence and Data processing: Reinterpretation/Better interpretation of potential EGS systems.
- Financing/Funding: e.g. crowdfunding schemes, insurance schemes, tax rate – also for technology. Proximity with demand is crucial and reduction of drilling costs ("drilling

insurance"). New report standards might be needed - metal + heat resources/reserves.

- Socio-environmental aspects: Different fluids might mean different procedures. Also, Long-term monitoring capacity should be developed.

Besides geothermal and mineral sector specific interest areas, a number of overarching topics were also identified, relevant for both sectors:

- Political, social, environmental background: land use planning, public education and outreach, labour market attractiveness/competitiveness (quality training, value for the profession), legislation and regulatory framework, public acceptance, induced seismicity, communication towards the public (common language, education, outreach).

At the very extreme, within the scope of the future oriented exercise, there was a mention about applying CHPM technology in extra-terrestrial environments for in-situ resource utilization. It was agreed that this topic may have relevance only beyond 2050.

These results fed into the preparation for the Delphi survey with organising, narrowing, and further defining the emerging topics that was presented to the Experts.

## 5. Delphi survey

The Delphi 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). Nowadays, Delphi expanded into a variety of modified approaches. However, at its core Delphi stands out as a reliable method in situations where individual judgements must be tapped and combined to address an incomplete state of knowledge. 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.

In WP6, the Delphi survey was used for input on important but uncertain areas in the future, in order to provide expert judgements in the face of uncertainty. It was the objective to work towards consensus on the future of areas with incomplete knowledge. The Delphi contained 2 rounds of surveys as an iterative process that assessed the long term (2050) applications of CHPM technology.

After the Lanzarote Horizon Scanning the workshop, LPRC worked with the partners' input and created the Delphi forms, using Google Forms. The statements and the form were reviewed and corrected by VITO (Ben Laenen), UNIM (Éva Hartai) and EFG (Anita Stein). Finally, 5 geothermal sector related, 4 mineral sector related, and 3 overall statements were selected to be used in the Delphi survey. More statements have been developed, but the final selection included only the following topics, one statement each (Figure 4).

**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

*Figure 4: List of topics in the CHPM Delphi survey.*

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, 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.

The final list of topics, including the actual statements in italics, and their relevance are listed below:

1. **Statement on drilling risk:** *Drilling risk is significantly reduced through better exploration techniques and experience in deep geothermal drilling.*

Geothermal drilling is the complex process of creating boreholes to access the geothermal resources (Finger & Blankenship, 2010). More than 50 % of the geothermal plants expenses are associated with drilling of wells (RHC-Platform, 2014), it is therefore crucial to minimise risk associated with drilling. Risk is composed of the probability of an event, and the severity of the impact when occurring. There are numerous types of risks associated with geothermal drilling, related to technology (geology, casing and cementing, equipment and tools, drilling material and consumables, etc), as well as H&S, environmental, financial, legal, organisational, policy and political risks (Okwiri, 2017). With CHPM technology, any of these risks may be relevant, but we will be mostly interested in the technical risks. Drilling risk is reduced along the learning curve as more experience is gathered in this field. Better exploration techniques, such as surface/geochemical/geophysical surveying, numerical and conceptual modeling, etc., yield better understanding about the geothermal site, therefore mitigating risk in the drilling phase (IGA Service GmbH, 2013).

2. **Statement on reservoir stimulation:** *Reservoir stimulation technologies (hydroshearing, hydrofracking, mild leaching, others) are commonly used in geothermal projects to increase well productivity.*

   There are already established technologies that can increase hydraulic conductivity within the reservoir rock mass, and therefore enhancing well productivity (CHPM2030 D1.4): hydraulic fracturing (conventional way to create fractures), hydroshearing (reactivating existing fractures at lower pressure), laser enhancement (use low energy loss high power laser devices to shock the rock and create fractures), leaching (chemical stimulation to increase near wellbore permeability (Nami et al. 2008). Reservoir stimulation is both technologically challenging and may evoke public resistance towards geothermal energy due to real or assumed environmental impacts.

3. **Statement on selective metal mobilization:** *Chemically enhanced geothermal fluids can selectively mobilize metals from below and keep it in solution until metals are recovered at the surface.*

This statement covers two aspect of metal winning from subsurface deposits, and both being crucial for the success of CHPM technology. Metal mobilization processes with added leaching agents (simulated geothermal fluid) has been investigated in WP2 and summarised in D2.2 Report on metal content mobilisation using mild leaching (CHPM2030 Deliverable 2.2). The metal recovery at surface is more efficient with high dissolved metal concentrations, however too high dissolved content may lead to early precipitation problems.

4. **Statement on geochemical processes:** *The complex geochemical processes (solution, precipitation, fluid-rock interaction, other) in the geothermal reservoir can be modelled and predicted for the lifetime of the CHPM project (20-30 years).*

   Fluid-rock interaction has been also studied in D2.2 Report on metal content mobilisation using mild leaching. It has been found that key uncertainties include lack of knowledge about the precise nature of mineralogy and fluid chemistry at relevant depths. It will be necessary to model or estimate these geochemical processes to have the basis for financial calculation on the expected metal production of the CHPM facility.

5. **Statement on corrosion:** *Geothermal instrumentation (well casing, downhole pumps, heat exchanger, other pipes) uses advanced materials that can resist to corrosive geothermal fluid.*

   Geothermal corrosion is a technological challenge when aggressive brines damage various parts of the installation. The corrosive effect of the geothermal fluids depends on the various chemical components of the brine: Hydrogen Ion (responsible for pH), Chloride, Hydrogen Sulphide, Carbon Dioxide, Ammonia, Sulphate, Oxygen (Miller, R.L., 1980 in Gunnlaugsson et al. 2014). Proper material selection (Kaya and Hoshan, 2005) and the surface-active inhibitors (Tomarov et al, 2005) can improve this issue, although the high cost of these solutions or manufacturing difficulties still remain to be addressed.

6. **Statement on geophysical methods:** *New and improved geophysical methods allow the accurate localisation of deep metal enrichments at great depths (> 6km).*

Very little geological data is available at the depths proposed by CHPM and indirect methods of prospecting are suitable for supporting initial identification of metal enrichments in the subsurface. Traditionally, most geophysical data has been presented in the form of contoured or raster plans and sections that can be interpreted in terms of geology and ore mineralisation they represent (Revuelta, 2018). In the last two decades, however, new methods were introduced generally referred as ‘data inversion’ methods.

7. **Statement on prospecting deep metal enrichments:** *Machine learning and artificial intelligence combined with predictive geological models are used for identifying different types of prospective metal enrichments with high confidence at great depths (~10 km).*

   Mineral deposit models have been traditionally created to describe the essential attributes or properties of a class of metal enrichments. For that, scientists observed a large amount of data in order to identify such patterns. These models therefore contain a level of prediction as they seek to capture transferable properties of known deposits to others alike. However, as CHPM deals with unexplored depths, where little geological data is available, prospecting in such conditions will require aid of advanced techniques that are able to recognise patterns, generate new models and make predictions, aligned with the regional geology knowledge available. Recent developments in Machine Learning and Artificial Intelligence can signal an important avenue for allowing successful exploration under such conditions.

8. **Statement on funding:** *Mining sector investors are the main drivers for CHPM projects development.*

   Mining is a capital-intensive industry oriented for economies of scale. Therefore, capital costs involved in mining are relatively high, which steady strong requires robust finances and access to capital. Compounded to this factor are the current challenges facing the mining industry, such as increasing operating depths, clean and cheap energy supply and social pressures for environment-friendly approaches. Such backdrop could be potentially suitable for the mining industry to drive further initiatives such as CHPM.

9. **Statement on deep drilling:** *Mining companies routinely drill for mineral exploration down to great depths relevant for CHPM technology.*

   Mining companies have been going increasingly deeper in their operations and exploration campaigns. The trend points to more underground operations and at greater depths. The main uncertainty therefore is how deep mining companies will go over the next decades.

10. **Statement on public opinion, SLO:** *The public is against Enhanced Geothermal Systems due to concerns about environmental impacts (e.g., induced seismicity, emissions, long term effects, etc.).*

    This statement was formulated intentionally in a provocative way to encourage free commenting. Social Licence to Operate is the informal agreement that infers ongoing acceptance of an industrial or energy project by a local community and the stakeholders affected by it (Gallois et al, 2017). Besides many environmental advantages of geothermal energy (low gaseous emissions, land usage, solids discharge, water usage, water pollution), there are potential negative environmental impacts too (land subsidence, induced seismicity, induced landslides, noise pollution, disturbance of natural hydrothermal springs, disturbance of wildlife habitat, vegetation, and scenic vistas, thermal pollution) (DiPippo, 2012). The local public may raise concerns over the potential negative effects, in spite of the numerous benefits of geothermal energy.

11. **Statement on investment risk:** *Expected revenue streams from metal recovery completely eliminate drilling risks associated with conventional geothermal development.*

    Potential revenue from the metal recovery can financially compensate associated drilling risks of technical nature. This statement meant to provoke thinking over the interrelationship between non-technical (financial) and technical (drilling risk) factors.

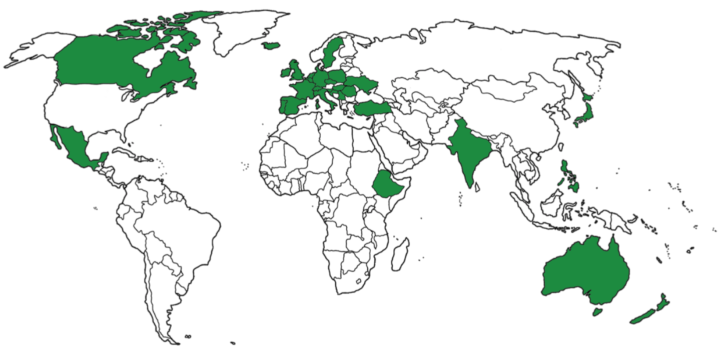
12. **Statement on market potential:** *CHPM technology is highly successful but reaches moderate market penetration only due to the low number of suitable formations where it could be developed.*

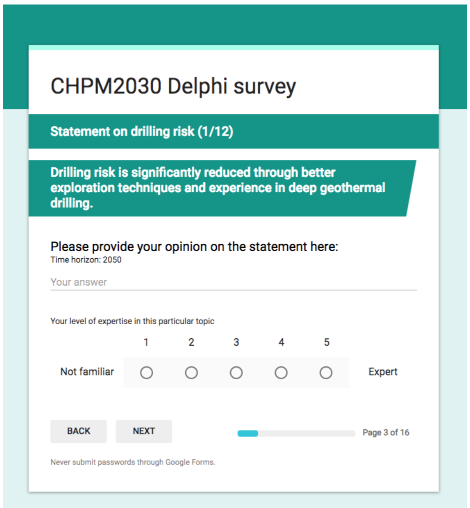
The economic feasibility of each CHPM target area is a critical success factor. The size of the market share, dependent on the size of suitable areas and how frequent they are geographically. A feasible combination of power, heat and metal recovery generation may be rare or abundant in terms of frequency and scale.

13. ***Bonus statement:*** *The first permanent settlement on Mars uses CHPM technology to satisfy its needs for energy and metals.*

    This statement has no direct relevance to the immediate project objectives and may have impact only beyond 2050. However, the topic also came up during the Lanzarote horizon scanning workshop, therefore the statement was included to inspire some out of the box thinking concerning the application of CHPM technology in the far future.

Parallel to transforming the Horizon Scanning results into Delphi statements, an Expert database was gathered, that included an open "Call for Experts" social media campaign. Many of the contacts were from the Company and Expert Pool[6] of the International Geothermal Association. Since some of the statements were very specific, e.g. on reservoir stimulation, the survey was split into 3 forms. One form contained only the geothermal sector related and overall statements, the second form contained only the mineral sector related statements and the overall statements, and finally only the third form contained all of the statements. This way the relevant statements were sent to the experts with relevant background.






6 https://www.geothermal-energy.org/explore/company-expert-pool/

*Figure 5: participation in the survey and the form from the 1st round*

The results of the 1st round were processed by LPRC and were integrated to the new 2nd form. The 2nd round has been sent to all previous participants and to the ones contacted earlier. Additional input fields were added: time horizon and previously identified emerging issues. The 2nd round of the CHPM2030 Delphi survey was closed and LPRC has processed the results, presented in this report.

At the end of the Delphi surveys, participants were also asked to suggest locations(s) where CHPM technology could be applied, given that there is a deep mineral enrichment and geothermal potential. There were many new ideas for applying CHPM technology in Europe and worldwide. The list of proposed locations for CHPM application and corresponding participants are presented in Annex 2).

The invitation reached ~1120 Experts through the consortium partners, Advisory Board members, Call for Experts social media campaign, EFG EurGeol mailing list, EFG Panel of Experts[7] on Minerals and Geothermal Energy, EFG Linked Third Parties[8], IGA Geothermal Expert Pool, Geochemistry of Geothermal Fluids Workshop[9] participants, IRENA Expert group, CHPM2030 and LPRC website, Twitter, Facebook and LinkedIn channels. In total ~133 Experts participated in the survey, worldwide (Figure 5), in either rounds, providing insights on emerging technologies and issues, future trends and expert opinion on critical areas.

[7] https://eurogeologists.eu/european-network/
[8] https://www.chpm2030.eu/partners/
[9] https://www.chpm2030.eu/workshop-geochemistry-of-geothermal-fluids/


*Figure 6: Delphi survey posts from ThinkGeoEnergy website.*

In this respect the CHPM2030 Delphi survey also served as an important dissemination tool, reaching a wide audience. The survey was also shared at the ThinkGeoEnergy[10] website (Figure 6).

In terms of presentation of the statements and forms design, in the first round, after an introduction page, it contained the topic, statement, comment field and self-assessment bar where the participants could provide their level of expertise on the given topic. The second round form already contained the results and statistics of the previous round, including the topics, the (original) statements, a summary of the first round, statistics, highlights of the previous comments, the (updated) statement, time horizon for the realization of the statement, list of previously identified emerging issues for voting (agree - no opinion - agree), comment field, and the self-assessment bar (Figure 7). On the last page of the survey, the participants had the opportunity to propose potential locations for CHPM implementation, to provide their name/institution to be acknowledgment in this report, and to provide their email address to receive the results of the survey in the form of this report. The participants

[10] http://www.thinkgeoenergy.com/

were informed that all this information was collected on a voluntary basis, only for the above-mentioned purpose.

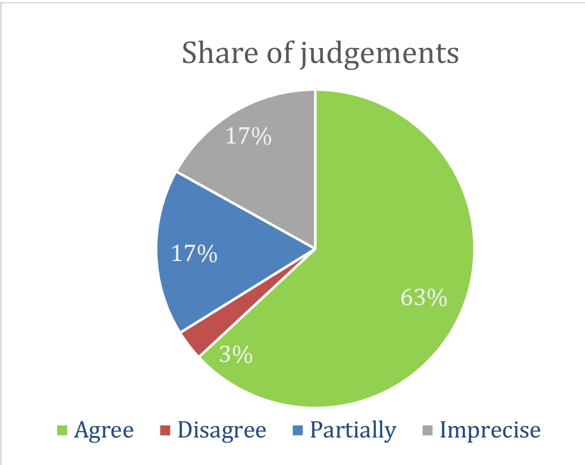

*Figure 7: Presenting a statement in the second round.*

In the following, the results of the 12+1 statements are presented and summarised. This evaluation contains a short summary of the first-round comments together with statistics and example comments. From the second round a short summary, statistics, reflection of the emerging issues from the first round, and other emerging topics and interesting comments are presented.

## 5.1. Statement on Drilling Risk (1/12)

***→ Drilling risk is significantly reduced through better exploration techniques and experience in deep geothermal drilling.***

~60 % of the experts agreed on the statement (Figure 8). Drilling risk is a bottleneck in geothermal development that has to be improved, however some drilling risk will stay. Also, seeking for cooperation with the Oil & Gas industry is highly desirable.




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | - | 4,0 | 4,0 | Mode |
| 3,5 | 3,5 | 3,5 | 3,5 | Average |

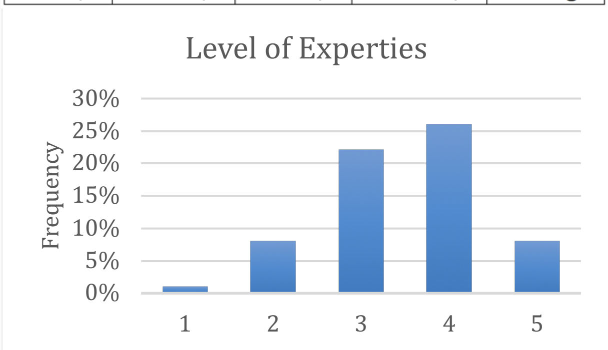



*Figure 8: Statistics from the Delphi round 1, statement 1/12*

Highlights of first round comments:

- *„Drilling technology will enhance - but the risks will stay."*
- *„Especially large experience of drilling in a specific rock type can reduce risks and costs by a factor of 2 or more."*
- *„The real risk lies for the moment in our ability to predict over the long term the thermal and mineral productivity of a well."*
- *„Geothermal energy needs to be develop in deep sedimentary basins where Oil & Gas industry has a much higher degree of competences that geothermal. Therefore, cross-over between geothermal and O&G has to be done."*
- *„A technological spillover between the two industry (geothermal and O&G) will be extremely desirable in order to gain mutual benefit."*
- *„Drilling risk is mitigated through an understanding of available offset data, seismic interpretation, geomechanical data, and overall geological interpretation."*

After the first round, the statement was updated, as the drilling risk was sometimes interpreted with either financial or technological origin. New statement: *Technological drilling risk is significantly reduced through better exploration techniques and experience in deep geothermal drilling.*

94% of the experts agree that the statements can be realised by 2050, and 50% of them says it will happen as early as 2030 (Figure 9). The two main insight streams were cooperation with the Oil & Gas or mining industry (to identify geothermal as an alternative business case, and adaptation of drilling technologies) and development of new drilling techniques and materials (deep cementing; bit development and rig design for faster drilling and lower costs; high temperature (350 °C) proof equipment). Better exploration workflows, insurance industry and better data storage and management for drilling and subsurface data also came up that has the potential to de-risk drilling operation for geothermal energy.

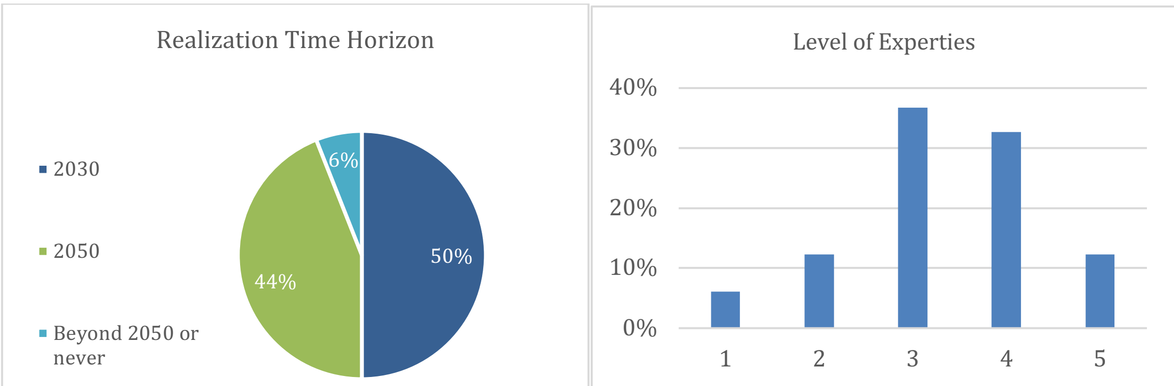



*Figure 9: Statistics from the Delphi round 2, statement 1/12*

During the first round there were 4 distinct topics identified (Figure 10), as emerging issues that were included in the second round for voting: disagree - no opinion - agree. This approach was useful for reaching consensus on some of the emerging issues. The ones highly agreed on were further included in the foresight process (Visioning), and the ones with high level of disagreement, proved to be less important. The ones with no opinion may indicate that the issue is not relevant or there is a lack of knowledge on how that particular topic has an impact of the main theme.

Issue 1: Cooperation with O&G sector for mutual benefit: technology spill over and sharing experience in deep drilling.

- *"Problem of risk vs reward: oil and gas reward is much higher"*
- *"Oil and Gas Companies will have to identify the field of deep Geothermal as possible business cases"*

Issue 2: Experience of drilling in specific rock type and deep sedimentary basins.

- *"Cooperation would be good, but O&G works at sedimentary basins, which have poor metal enrichment"*

Issue 3: Better data interpretation: understanding of available offset data, seismic interpretation, geomechanical data, and overall geological interpretation.

Issue 4: Better data acquisition: improved geophysical exploration methods.

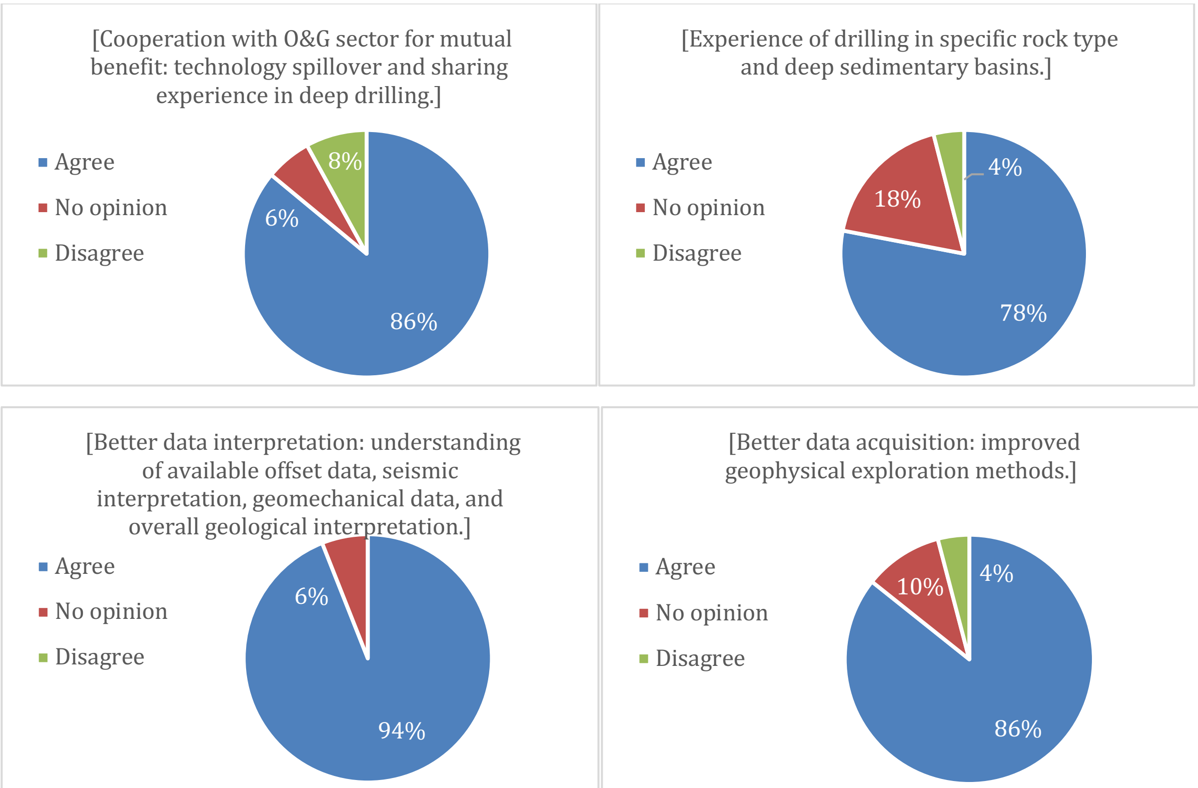



*Figure 10: Agreement on emerging issues, round 2, statement 1/12*

Some of the emerging issues from the second round, related to e.g. developments on drilling techniques and materials, are listed as the following:

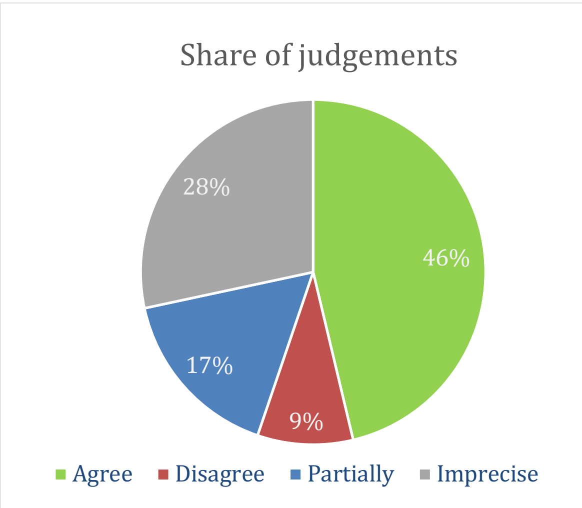
- *"Improvement in deep cementing".*
- *"Bit development and rig design: faster drilling, reduced cost*

- *"Tools / equipment / materials are limited to 180 celsius, we need drilling, logging technology, drilling fluids, cementing, casing materials and couplings as well as well integrity issues in wells experiencing temperatures above 350 deg*
- *"Optimise processes through: Real-time drill-rig awareness, smart drill-rig, ML, autonomous drilling rig*
- *"Drilling risk depends on: 1) geothermal system properties, and 2) pre-drill knowledges*
- *"Better exploration workflows are needed to reduce risk*
- *"Success or failure in drilling are due to three major aspects: planning, execution, and supply chain.*
- *"Geothermal hydrological model that is critical*

### 5.2. Statement on Reservoir Stimulation (2/12)

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

The experts confirmed that these technologies are already applied for many decades in the geothermal and oil & gas industry, and only 9 % disagreed with the statement (Figure 11). Besides technological difficulties and potential environmental risks (e.g. induced seismicity), the major bottlenecks are the lack of political support and public resistance.




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

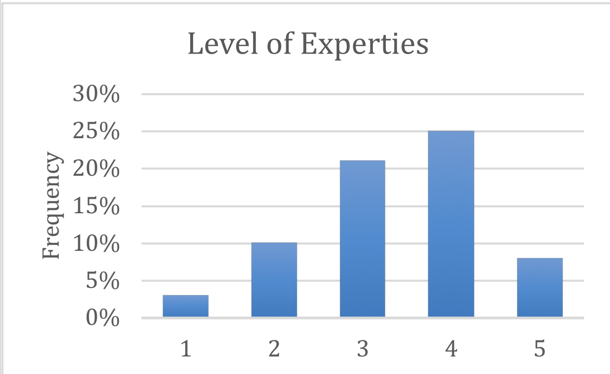



*Figure 11: Statistics from the Delphi round 1, statement 2/12*

Highlights of first round 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."*

In the second round, 54% of the experts agreed that these technologies will be commonly used by 2030, and another 36 % thinks it will be achieved by 2050 (Figure 12). Many of the concerns were related to social and political aspects, rather than technological challenges. Upcoming issues relates to SLO, Environmental impact and political support.

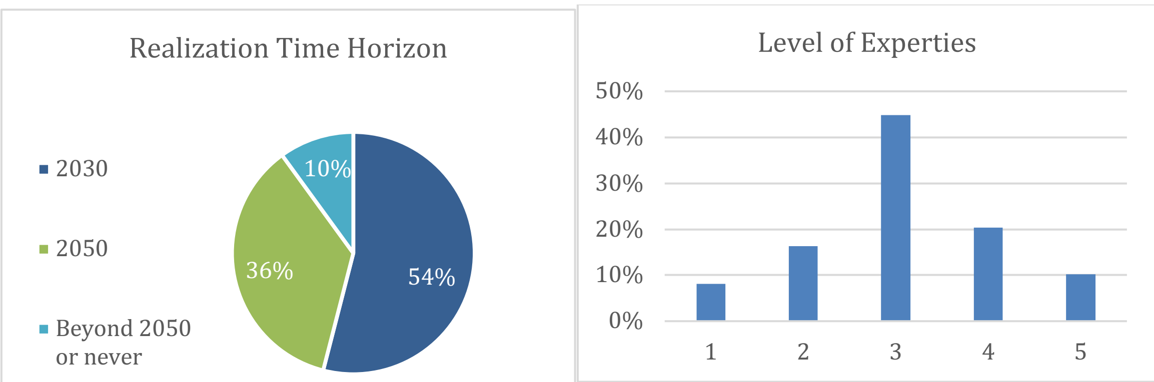



*Figure 12: Statistics from the Delphi round 2, statement 2/12*

During the first round, 4 issues has been identified to be used for voting and comment generation (Figure 13), related to Social Licence to Operate, environmental impact, political support for deep geothermal energy and stimulation impact for the far field (100-1000 m). The first two issue received many comments with high level of agreement, however the last one, many participants were unsure how to relate to this issue.

Issue 1: Social Licence to Operate from the public trough better communication and public involvement and understanding.

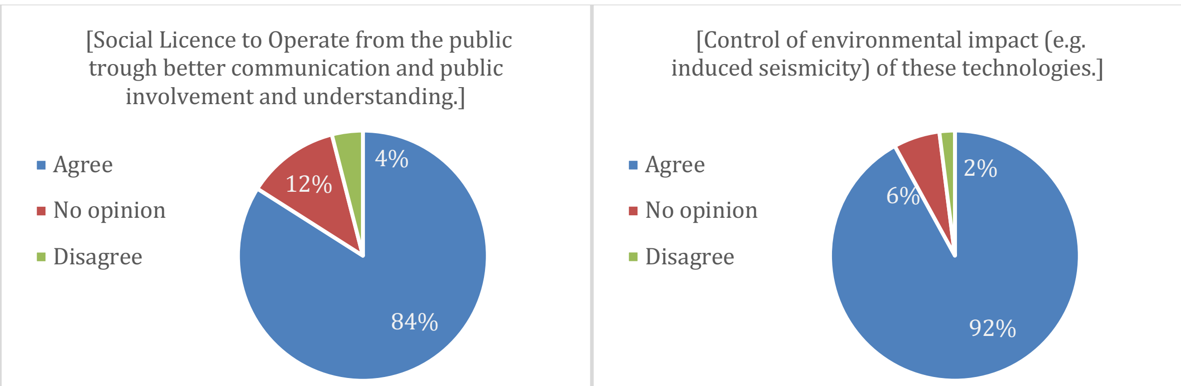
- *"'social licence to operate' as the greatest challenge. Factual arguments vs emotional objections, politically motivated? de-politicise reservoir stimulation."*
- *"I see rather social / political than technological problematic issues"*
- *"population needs to be educated to understand"*
- *"Must: examples of positive experiences of these methods for demonstration"*
- *"1) 'Hydrofracking' terminology 2) engage schools (info for parents too, + long-term) 3) Early successes greatly assist geothermal uptake, so it is vital to invest properly in the early schemes."*

Issue 2: Control of environmental impact (e.g. induced seismicity) of these technologies.

- *Control of environmental impact is key. If successful, public/political support.*
- *injection that is causing the increased seismicity.*
- *geothermal fields: active fault lines, young volcanic areas: may disrupt the balance.*
- *Induced seismicity is not a real issue it is widely under control*
- *constant field-wide monitoring*

Issue 3: Political support for deep geothermal energy.

Issue 4: Stimulation impact on the far field (100-1000 m distance).



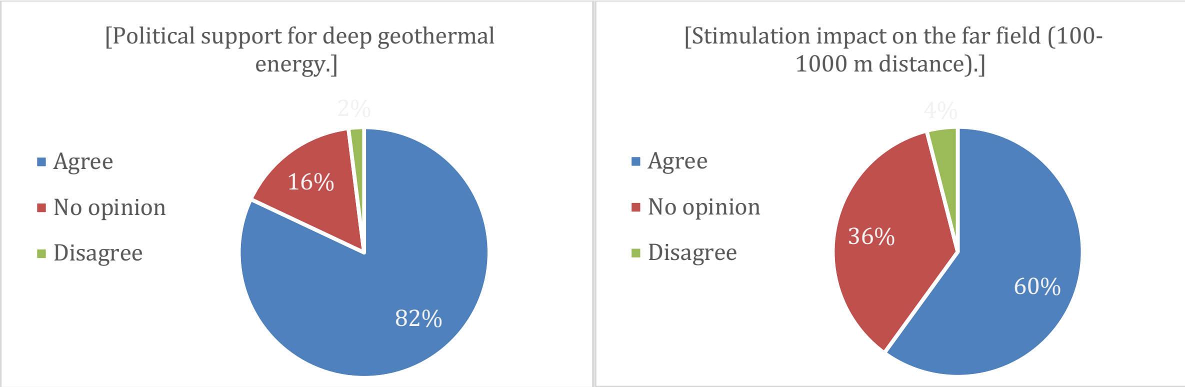



*Figure 13: Agreement on emerging issues, round 2, statement 2/12*

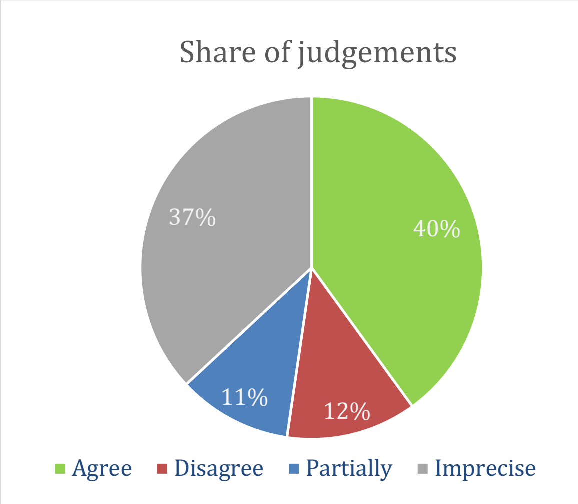
Some of the emerging issues from the second round, related reservoir stimulation, are the following:

- *"deflagration and radial-jet drilling."*
- *"Cost+SLO: expensive. Public acceptance of these techniques and maintaining economic viability."*
- *"social (general+political) support for these technologies and the uncertainty, or predictability of how these technologies impact."*

### 5.3. Statement on Selective Metal Mobilisation (3/12)

***→ Chemically enhanced geothermal fluids can selectively mobilise metals from below and keep them in solution until metals are recovered at the surface.***

This statement includes two defined elements: metal mobilisation is generally agreed to be feasible, however, keeping metals in solution probably proves to be a bigger challenge. It was suggested to use chemical solvents or chelants to avoid early precipitation. The potential environmental impact has to be closely investigated and to be proved safe. It was mentioned that mineral extraction from geothermal fluid is not a new idea, in Lardarello, Italy, extraction and processing of boron is already done. Extraction of Li is also a hot topic. Public opinion and cost of operation came up again in the comments. There was a high diversity on level of expertise self-assessment from the participants at this topic (Figure 14).




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 2,0 | 3,0 | 1,0 | Mode |
| 3,0 | 2,6 | 3,4 | 2,1 | Average |

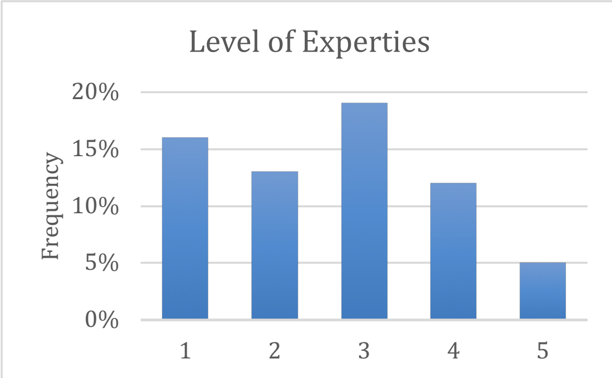



*Figure 14: Statistics from the Delphi round 1, statement 3/12*

Highlights of first round comments:

- *„It will also be important to demonstrate to local communities that any increases in dissolve metal concentrations will not provide an undue risk to local potable water resources."*
- *„Metals extraction from geothermal fluids is not something new. Larderello, where I work, was initially founded, for the extraction and processing of boron. lithium extraction from geothermal brines is another hot topic in geothermal industry nowadays."*
- *„We'll needed chemical solvents / chelants to ensure that the leached metals stay in solution."*
- *„The statement has two well defined elements. The former one is generally agreeable, the later one is the bottleneck of the CHPM technology."*
- *„This occurs in many locations already within the oil and gas industry to keep dissolved solids in liquid form until they can be removed post well."*
- *„The chemically enhanced geothermal fluids/ the chemical energy carriers (CEC) can capture more energy per unit volume of working fluid and deliver high exergy. Though CEC fluids can be used to mobilise metals selectively."*

In the second round, half of the respondents expect that this statement will become true by 2030 and altogether 92% believe that it will happen until 2050 (Figure 15). Similar to the previous round the upcoming issues were social and political concerns, element specification (elements will react differently), cost of operation, efficient methods of extraction at the surface, potential environmental impact.

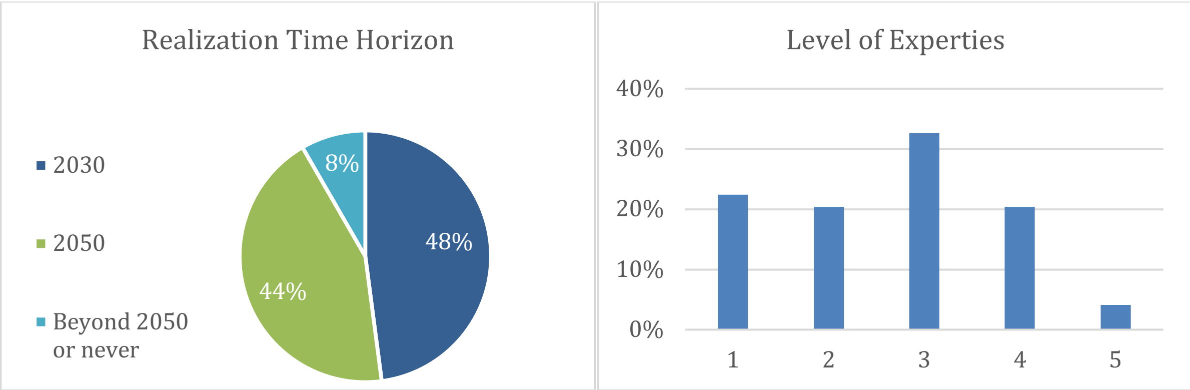



*Figure 15: Statistics from the Delphi round 2, statement 3/12*

There were 7 emerging issues debated in the second round (Figure 16), however the ones related to environmental impact got the most comments.

Issue 1: [Chemical energy carriers (CEC) to capture more energy per unit volume of working fluid and deliver high exergy.]

Issue 2: [Communication and awareness raising towards the general public.]

- *"Because if the general public is not properly informed, it can rise some issues that will affect our work."*

Issue 3: [Potential to mobilise radioactive minerals.]

- *"A key issue is selectivity, so that toxic or radioactive materials will be left behind in the reservoir.*
- *"We must consider as many precautions as possible, not to affect the quality of drinking water for the population."*

Issue 4: [Avoiding early precipitation, scaling in the pipes, heat exchanger, reservoir, etc.]

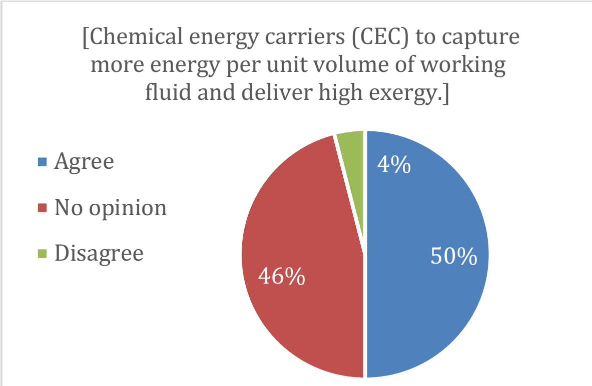
Issue 5: [Potential environmental impact of enhanced geothermal fluids.]

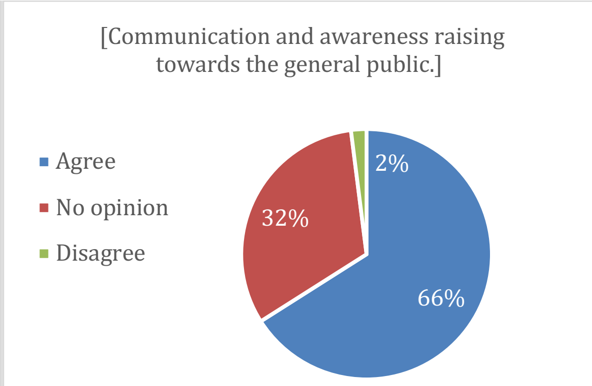
- *"Long term environmental impact of fluids must be investigated"*
- *"Social/political issues will be very important together with assuring local stakeholders that the CHPM plant do maximum to protect environment and groundwater."*

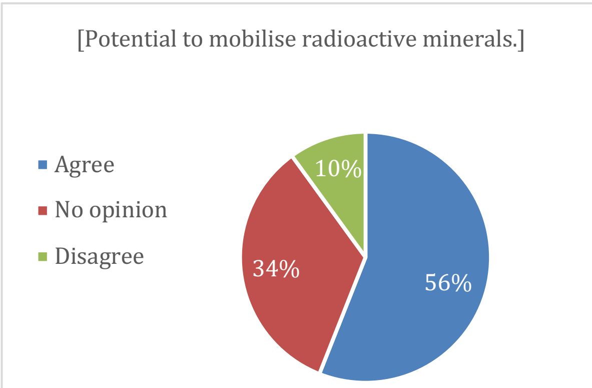
Issue 6: [Cost of chemically enhancing the geothermal fluid.]

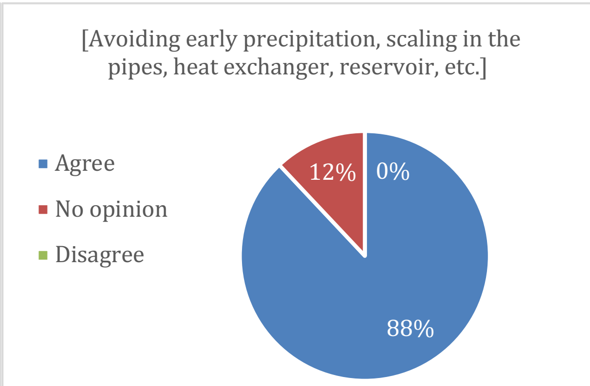
- *"A serious issue that I see is the likely cost of the operation."*

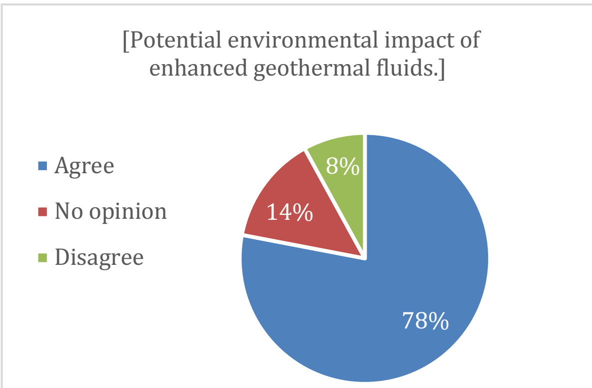
Issue 7: [Chemical solvents/chelants to ensure that metals stay in solution.]

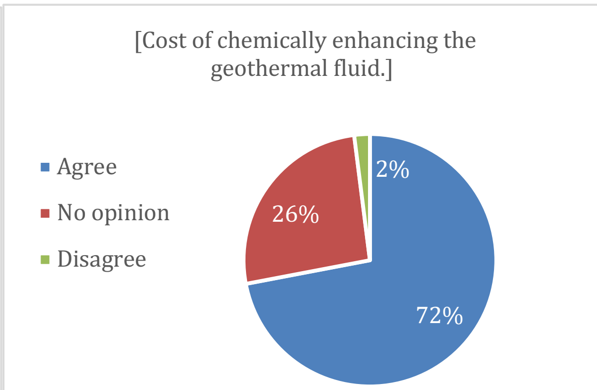


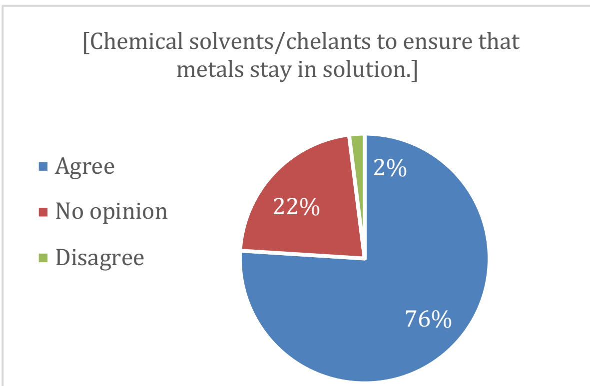
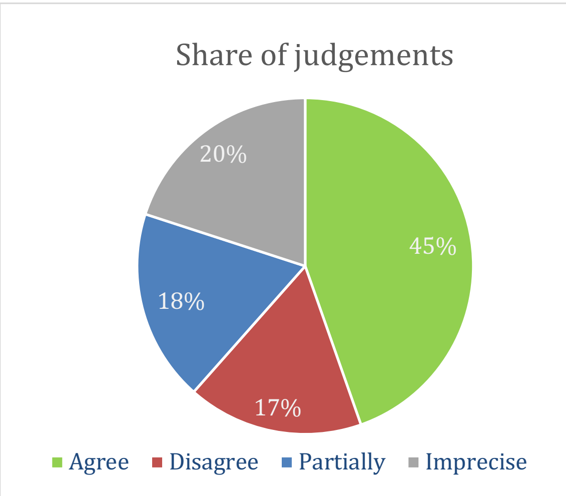



*Figure 16: Agreement on emerging issues, round 2, statement 3/12*

## 5.4. Statement on Geochemical Processes (4/12)

***→ The complex geochemical processes (solution, precipitation, fluid-rock interaction, other) in the geothermal reservoir can be modelled and predicted for the lifetime of the CHPM plant (20-30 years).***

Nature is unpredictable, however, according to the participants, with the advance of computing power, reactive-transport code, obtaining reliable input, advancement in geochemical and fluid-rock interaction research in the geothermal space, thermal - hydrological - mechanical- chemical modelling on reservoir scale may be achieved in the future. The role of geochemical modeling for techno-economic viability assessment was also mentioned. There was a relatively high level of disagreement here, compared to previous statements (Figure 17).




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 3,0 | 4,0 | 3,0 | Mode |
| 3,4 | 2,9 | 2,9 | 2,5 | Average |

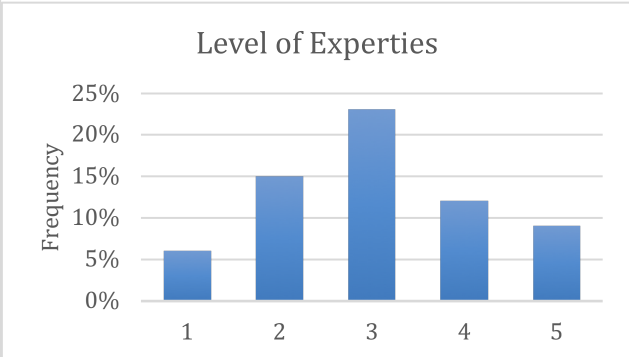



*Figure 17: Statistics from the Delphi round 2, statement 4/12*

Highlights of first round comments:

- *„Being able to model the solution / precipitation in the CHMP-reservoir will be crucial to asses the techno-economic viability. Reliable reactive-transport code for high-activity solutions is needed."*

- *,,I think much more needs to be done with the geochemical and fluid-rock interaction research in the geothermal space before anything can be modelled well enough for prediction of a resources lifespan."*
- *,,No, modelling a complex multi-species and multi-physics system for a long period is for the moment out of our capacities as it requires significant computing power, identification of too many reaction constants and parameters."*
- *,,All models and predictions the outcome of these models are only as good as the input data. So substantial research is needed to get reliable input data and verification and history matching processes."*
- *,,We must advance and put focus now on the Thermal - Hydrological - Mechanical - Chemical modelling on reservoir scale simulation."*
- *,,Yes, modelling capacity has been significantly improved in the recent times. The main limitations are thermodynamic and kinetic databases, which lack of information at high temperatures and high salinities. Also, accurate knowledge of the permeability of the media at depth and the main flow paths are usually poor and this introduces a large uncertainty in the model output."*
- *,,Chemical thermodynamic data necessary for such modelling are available for many aqueous species and minerals, and are reasonably good, up to 100°C or somewhat above, probably adequate for many purposes up to 250°C, but very sparse and often of dubious quality above 300°C. This is particularly true of the dissolved aqueous species. (...). At high concentrations of dissolved chemicals, the activity coefficients of aqueous ionic species are poorly known and difficult to model. These activity coefficients essentially provide a relationship between the species concentrations and their free energy, and this information is essential. (...). For high-temperature geothermal fluids, or fluids with significant concentrations of dissolved chemicals, to be modelled adequately by 2050, much more thermodynamic data must be generated, and models of activity coefficients must be vastly improved."*

In the second round, 34% of the respondents expect that this statement will become true by 2030 and additional 50% believe that it will happen until 2050 (Figure 18). The main issue came up here is the availability of real input data about the reservoir fluid/rock chemistry, high-temperature chemical thermodynamic datasets. It was also agreed that basic research on geochemical and fluid rock interaction is important issue for future development. Probabilistic predictions could be used for future economic model.

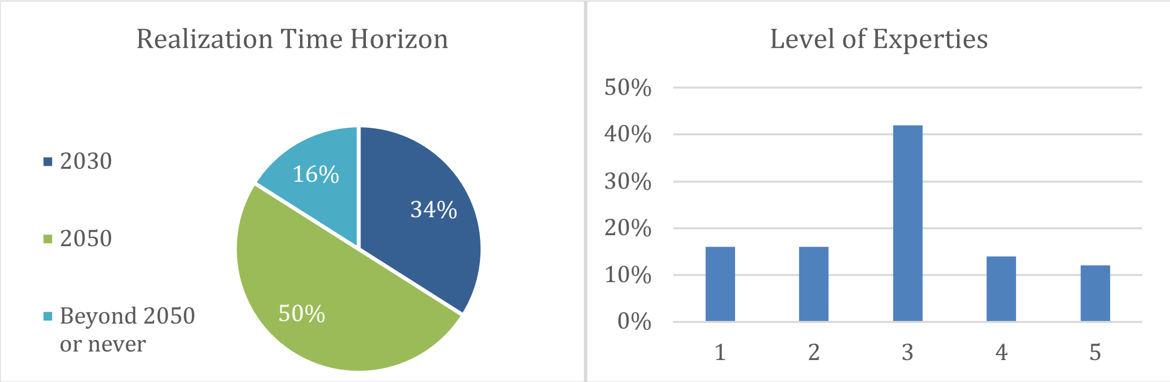



*Figure 18: Statistics from the Delphi round 2, statement 4/12*

Out of the 5 emerging issues (Figure 19), coming from the first round, the one about new thermodynamic data sets got the most comments.

Issue 1: Significant computing power (hardware) that can handle large scale models with numerous datasets and reactions.

Issue 2: Basic research on geochemical and fluid rock interaction.

Issue 3: Availability of new chemical thermodynamic data sets.

- *"thermodynamic data is probably the main challenge."*
- *"high-temperature chemical thermodynamic data, activity coefficient models, and knowledge of the kinetics of the processes involved."*
- *"computing power is for the most part adequate, however. The thermodynamic and kinetic data, and the activity coefficient models, are not."*
- *"The lack of data availability on fluid/rock chemistry and thermodynamics at the depth of the EGS plant can be the main limitation in modelling*
- *"The difficulty here could be to get accurate input data from the reservoir."*
- *"any modelling and predictions especially in long term period will be very dependent on the real input data."*

Issue 4: Thermal-Hydrological-Mechanical-Chemical modelling on reservoir scale simulation.

Issue 5: Reliable reactive-transport code for high-activity solutions.

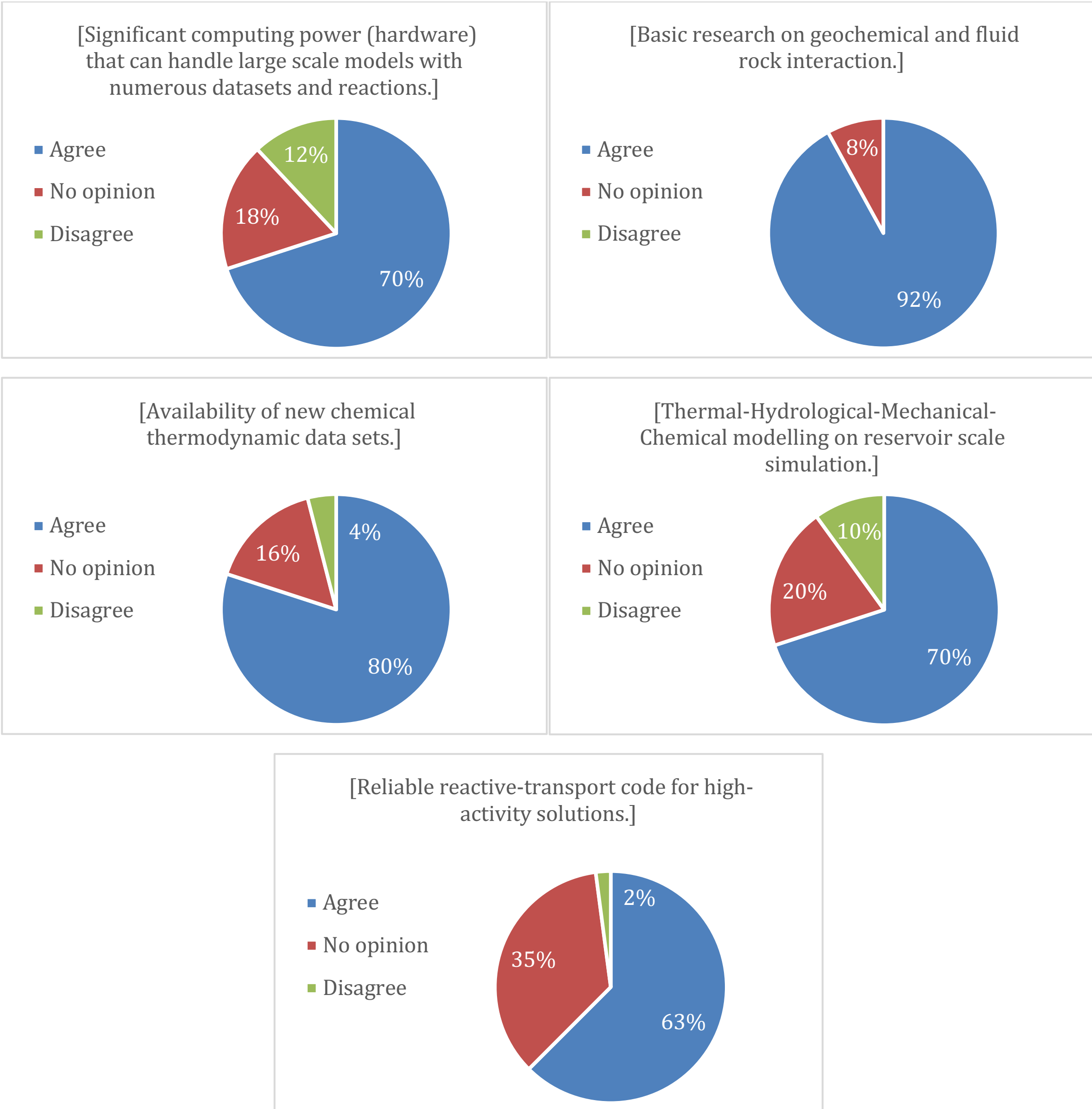



*Figure 19: Agreement on emerging issues, round 2, statement 4/12*

Other emerging issues identified in the second round, related to modeling geochemical processes are the following:

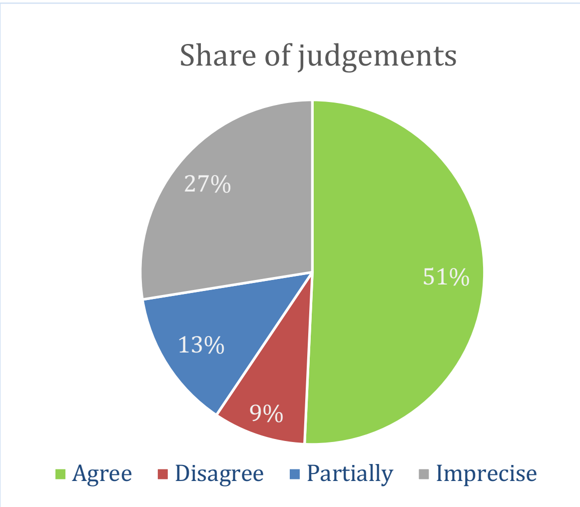
- *probabilistic modelling of the full system. Probabilistic predictions of future production fit neatly into economic models to give a financial risk profile.*
- *need demonstration projects and a history matching evaluation: small scale than real scale*
- *The 3 key enablers I've selected can all be used to feed/boost models developed (and tested) by AI ([Basic research on geochemical and fluid rock interaction.] [Availability*

*of new chemical thermodynamic data sets.] [Thermal - Hydrological - Mechanical - Chemical modelling on reservoir scale simulation.])*

### 5.5. Statement on Corrosion (5/12)

***→ Geothermal instrumentation (e.g. well casing, downhole pumps, heat exchanger, other pipes) use advanced materials that are resistant to corrosive geothermal fluids.***

When it comes to lifetime of geothermal instrumentation, not only corrosion, but scaling can also be a major issue. With proper material selection, corrosion can be avoided, although it can be expensive, so the next research objective could be to bring these costs down. Ongoing H2020 funded projects, such as GeoWell[11], GEMex[12], are investigating new material technologies and the development of corrosive resistant materials. It was also mentioned that metal-mineral interaction is an under-researched topic. 51 % of the respondents agreed with the statement (Figure 20).




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 4,0 | 3,0 | 3,0 | Mode |
| 3,1 | 3,4 | 3,1 | 2,8 | Average |

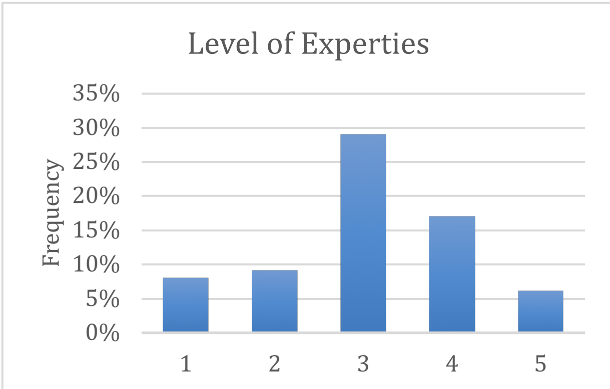



*Figure 20: Statistics from the Delphi round 1, statement 5/12*

Highlights of first round comments:

- *„Corrosion-resistant materials have always been available; it is the cost that makes it prohibitive."*

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[11] http://geowell-h2020.eu/

[12] http://www.gemex-h2020.eu/index.php?lang=en

- *,,I think there is a huge gap in the geothermal industry when it comes to metal-mineral interactions and interfaces. This is a materials science question that is under-researched..."*
- *,,No, this statement is most usually not true. Current well completion techniques are far from perfect and do not provide good corrosion resistance. (...) European projects such as Geowell and GEMex are now investigation new corrosive resistance materials for deep geothermal application as well as new completion approaches."*
- *,,Normally yes. Downhole pumps is, in my experience, the most sensitive instrument to chemical changing (scalings can disturb the pumps extremely)."*
- *,,Yes, material technology is already a topic in several EU supported H2020 geothermal projects and this is likely to result in improved material selection, although relatively high prices may hinder a rapid development in this field."*
- *,,Yes, though scaling is still a major challenge/cost. New technologies are evolving to bring those costs down."*

In the second round, 62% suggests corrosion will not be a problem by 2030, and another 28% agrees that it will be solved between 2030 and 2050. 10% remains that it will not be solved by 2050 (Figure 21). It was agreed that cost of advanced materials will need to be reduced. The use of selective isolation, chemical treatment/injection. On the other hand, early precipitation is even bigger issue, which is a function of fluid physical chemistry/ thermodynamics.

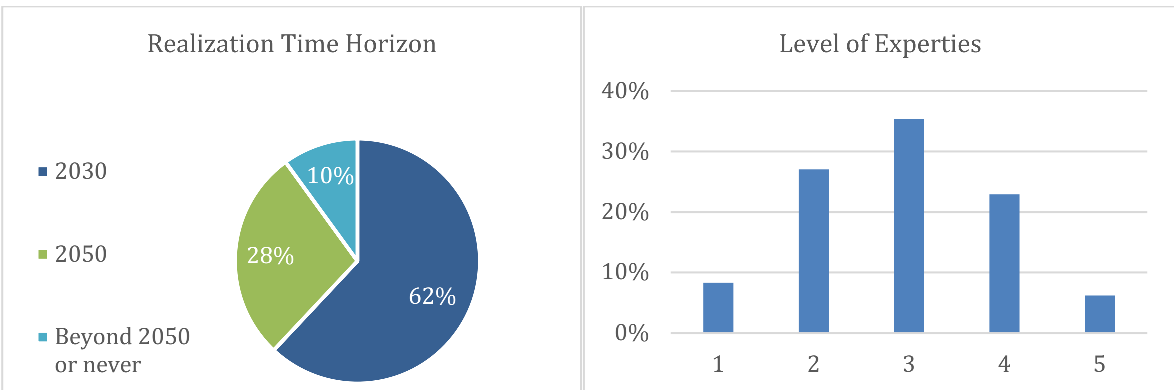



*Figure 21: Statistics from the Delphi round 2, statement 5/12*

During the first round there were 4 topics identified (Figure 22), as emerging issues that were included in the second round for voting: cost of corrosion-resistant materials, metal-mineral research field, downhole pumps, precipitation/scaling. The first and last issue received many comments, while participants did not associate with the issue regarding downhole pumps. There was a low level of agreement weather the metal-mineral interaction is an under-researched topic or not.

Issue 1: Cost of selected materials is the bottleneck to select corrosion-resistant materials.

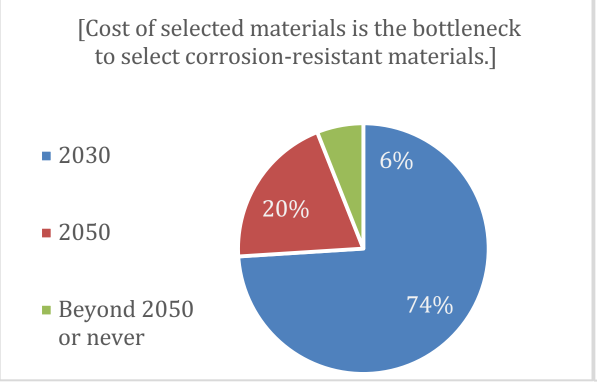
- *"Cost that limit the use of expensive corrosion-resistant materials. It is highly desirable to make such materials much cheaper."*
- *"Cost reduction: One possible way is to use cladding i.e. covering the conventional steel pipe of production section with corrosive-resistant layer."*
- *"Corrosion the materials are available but expensive."*

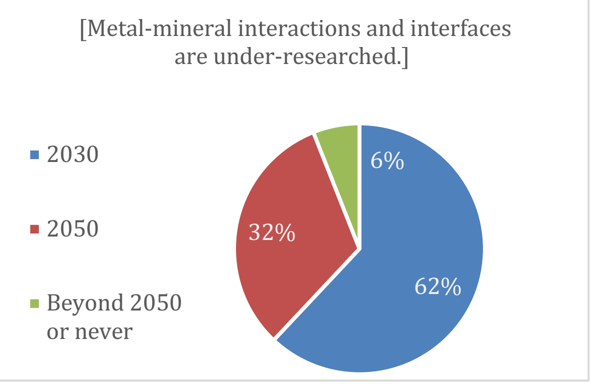
Issue 2: Metal-mineral interactions and interfaces are under-researched.

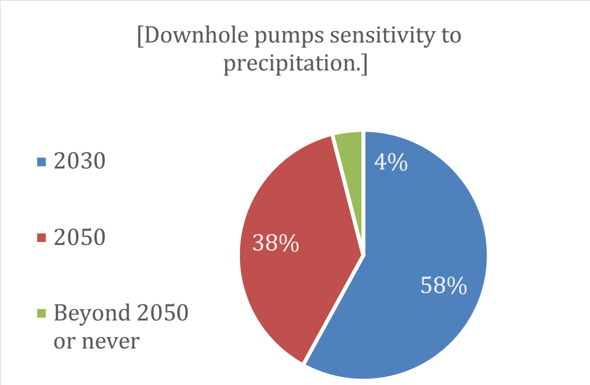
Issue 3: Downhole pumps sensitivity to precipitation.

Issue 4: Precipitation is an even bigger issue when it comes to saline geothermal brines.

- *"Scale formation inside the well is a function of fluid physical chemistry/ thermodynamics ONLY."*
- *"Keeping the minerals in solution is a bigger challenge."*
- *"More research is due on precipitation and inhibition of precipitation."*





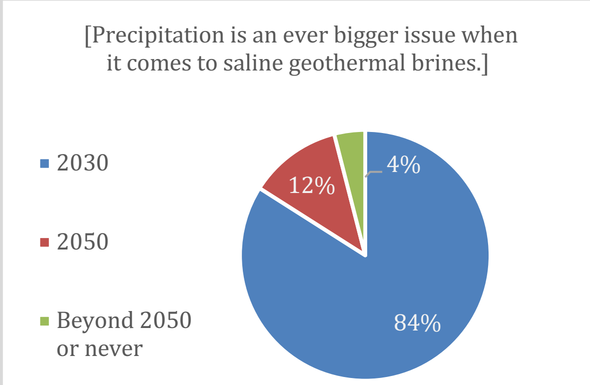




*Figure 22: Agreement on emerging issues, round 2, statement 5/12*

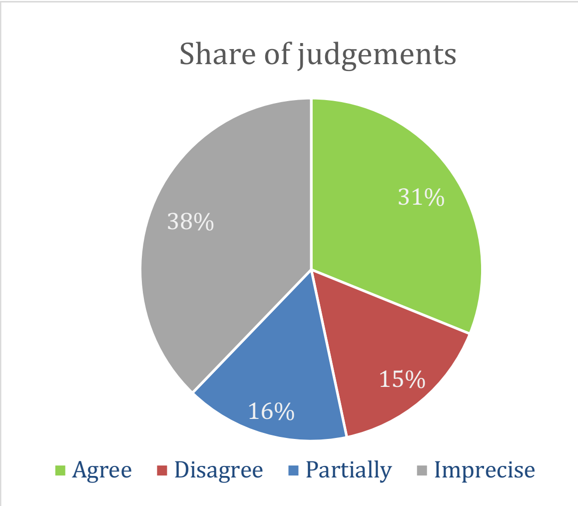
Some other emerging issues identified in the second round, related to corrosion, materials selection and are the following:

- *"Corrosion issues downhole can be remedied by selective isolation, chemical treatment/injection."*
- *"Conventional steel casing is used and as far as i can tell this will not change for at least 20 next years."*
- *"Use of other materials, e.g. fiberglass."*
- *"Linear expansion of tubes due to heat is also a challenge."*

### 5.6. Statement on Geophysics (6/12)

***→ New and improved geophysical methods allow the accurate localisation of deep metal enrichments at great depths (>6km).***

This statement provoked reflections on conceptual aspects of metal enrichments and enablers such as data processing techniques. It was also acknowledged that there is a need for intensive research in the field. There was a high convergence of opinions on the expected improvement of geophysical methods (in quality and depth achieved). More divergence occurred on the level of improvement and the results they can generate. The most common issue raised was related to the types of mineralisation: for the statement to be true this would be highly dependent on the type of mineralisation (or enrichment). That is, massive, higher density sulphides and magnetic minerals would be easy to handle as opposed to disseminate and low-grade material.




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 4,0 | 2,0 | 3,0 | 1,0 | Mode |
| 3,4 | 2,4 | 3,1 | 2,5 | Average |

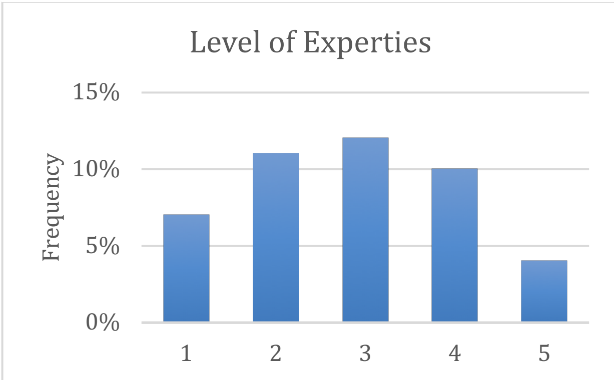



*Figure 23: Statistics from the Delphi round 1, statement 6/12*

Highlights of comments:

- *"Extensive need for research in this area still needed - big gap in turning geophysical methods into practical use. One respondent pointed out that there might be a gap in data processing (i.e. noise reduction, reflection etc.) more than a gap in data acquisition capacity."*
- *"New and improved geophysical methods will demand a combination of data processing techniques (software) plus powerful instruments and precise receptors (hardware)."*

In the second round, half of the respondents expect that this statement will become true by 2030 and another 32% believe that it will happen until 2050.

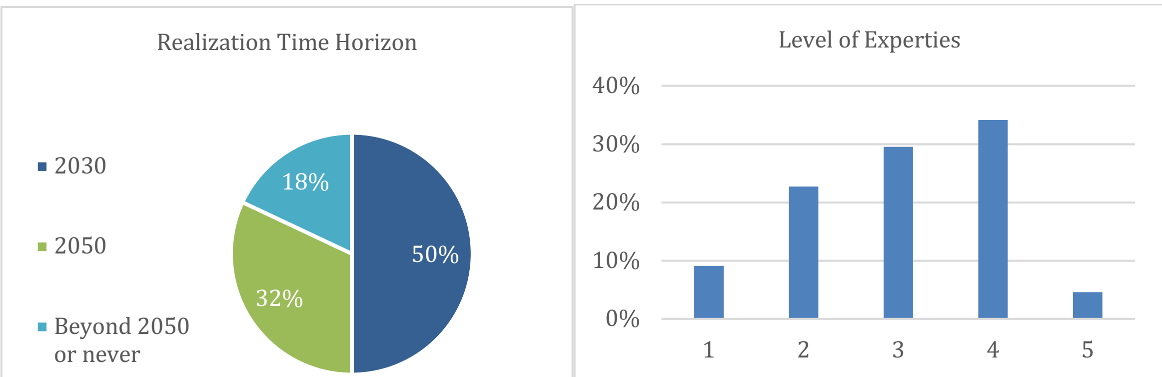



*Figure 24: Statistics from the Delphi round 2, statement 6/12*

In general, there is optimism given modern developments of geophysical methods, instruments and data processing tools and software. However, the suitability of some targets for geophysics utilisation will still be a factor to consider.

In summary of the identified issues: appropriate geological models are required for geophysical investigation - new depths might require new models or a general geological study first. Only some targets would be suitable for the usage of geophysical methods - or different metals might need different geophysical methods (Figure 25). Exploration hardware will not improve as much as exploration software. Great depths mean great scale of (seismic?) noise to surface instruments - geodynamical history of the area vs. geophysical improvements.

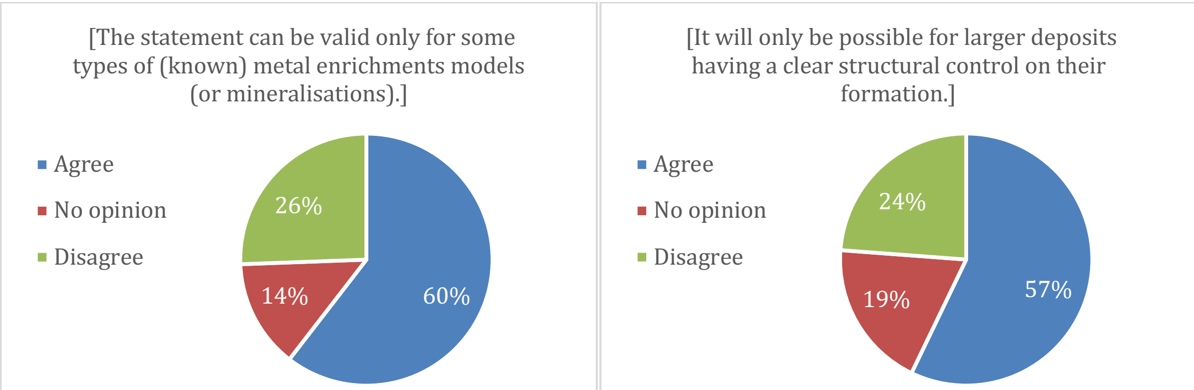



*Figure 25: agreement on emerging issues, round 2, statement 6/12*

Highlights of comments:

- *"Highly mineralised zones may well have permeability sealed by that mineralisation. What is key is an open fracture system to enable heat extraction, and just enough mineralisation to saturate the fluid with metals for the lifetime of the EGS - any more metal will simply not be recovered. Thus lower grade deposits (i.e. harder to detect) may in some circumstances be better targets than highly mineralised systems."*
- *"I expect exponential growth in the interpretation of even noisy or poor geological and geophysical data with the use of ML and AI and significantly larger computing power. In terms of "exploration hardware", it will improve too, but not as exponential as the "exploration software""*
- *"I think that one of the biggest problems to reach this statement is the knowledge of scale transfer of properties recorded by surface instruments. More far is the targeted*

*source, more diluted is the signal from this source. In consequence, inversion of surface data lead to many solutions in which the real one could be find (or not). Maybe geophysical records in existing deep well from geothermal fields could help to improve accuracy of ore localisation within the close environment of the well. A comment close of the subject: Do not forget that a very good knowledge of geodynamical history of an area could be more useful than geophysical improvements to locate resource at great depth. It is more prevalent to find what you search than to find somewhat of unexpected."*

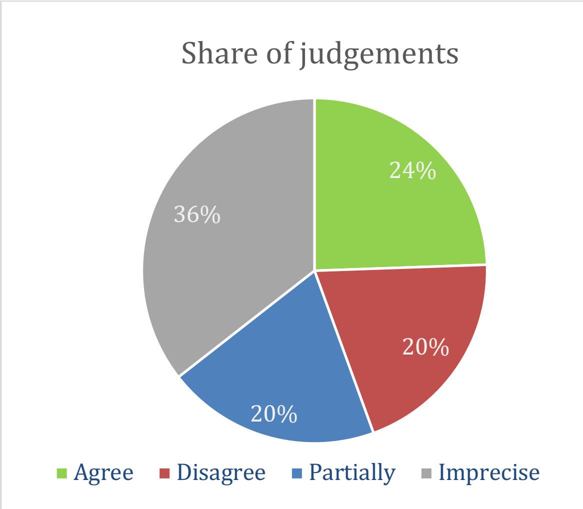
- *"New geophysical techniques are combining Seismic, Satellite Remote Sensing, Gravity, Magnetic and Resistivity. With this combination you can find any important reservoir, heat source, mineralization or any important metal deposits below 6 km. Just the right question will this reservoir feasible for the geothermal investment. Maybe after 10 years will it feasible and until this years geophysical methods, data processing and software will be able to find it at the right location."*

### 5.7. Statement on AI and ML (7/12)

***→ Artificial Intelligence and Machine Learning combined with predictive geological models are used for identifying different types of prospective metal enrichments with high confidence at great depths (~10km)***

Many comments showed concern over the level of confidence and suggested depth. It was also acknowledged the incomplete knowledge on artificial intelligence and how it could be employed, similarly to the previous statement. The lack of availability of data at such depths might be an important barrier to apply AI and machine learning to aid prediction with high confidence.

The most commonly raised issues related to deposits that can still escape predictive models and confidence at depth of 10 km. Deposits that escape predictive models - for this statement to be true, geological knowledge at such depths should be enough to feed the algorithms so it can recognize patterns and successfully identify potential targets. High confidence/depth of 10km - the depth and level of confidence are interrelated and gauging the ambitions to the developments in AI and ML is particularly challenging.




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 3,0 | 3,0 | 3,0 | Mode |
| 3,0 | 2,6 | 3,4 | 2,6 | Average |

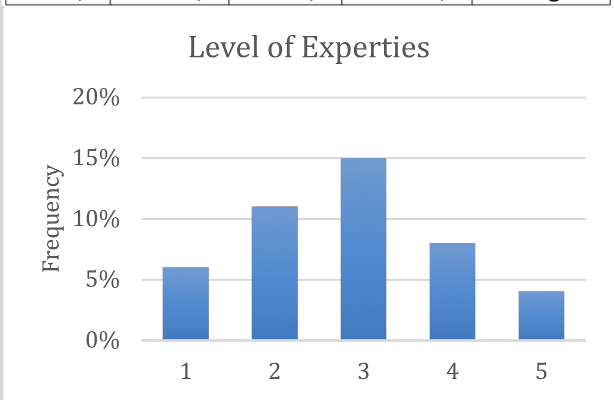



*Figure 26: Statistics from the Delphi round 1, statement 7/12*

Highlights of comments:

- *"Models would only be valued if combined with geophysical methods and drilling."*
- *"New paradigm in data processing in geosciences is needed"*

In the second round, almost half of the participants (46%) believe that this is not becoming true by 2050 or beyond (Figure 27).

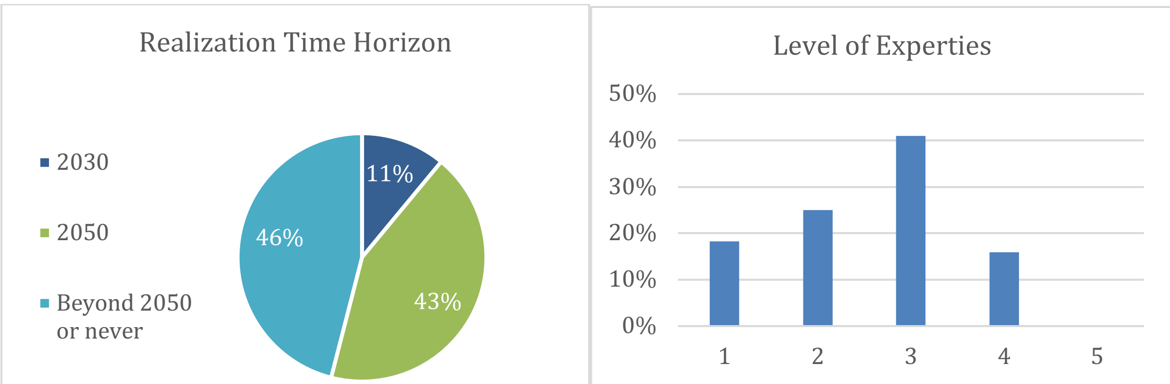



*Figure 27: Statistics from the Delphi round 2, statement 7/12*

Some scepticism over how and when AI and ML would turn the statement true is also confronted with the acknowledgement of the potential that these tools could have when looking further into the future.

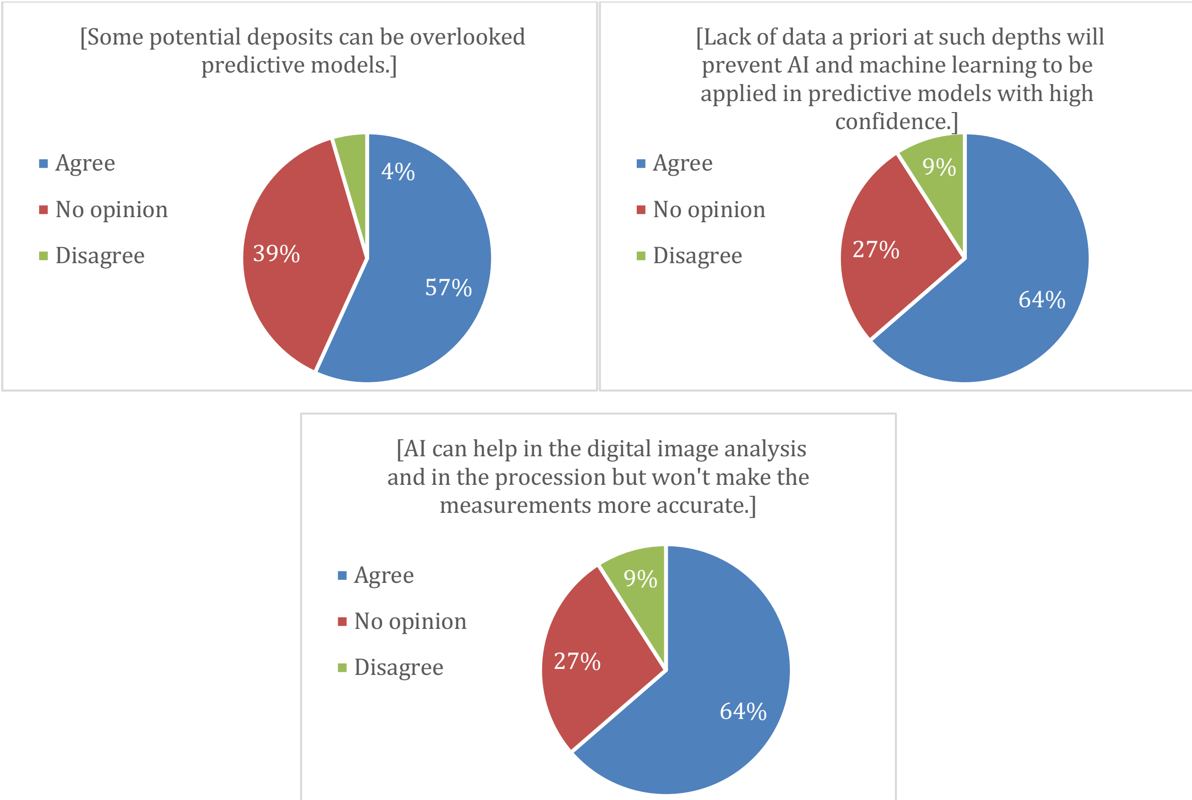



*Figure 28: Agreement on emerging issues, round 2, statement 7/12*

In summary of the identified issues in the second round: it was found that new theories on bedrock development in different structural domains (or greater depths) will emerge. Human interpretation and expertise will still be critical - AI still much "under-researched". Drilling depths still a constraint - field materials are required after all for developing predictive models.

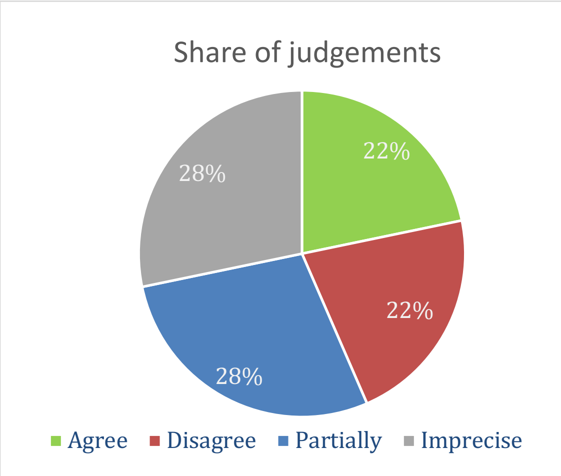
Highlights of comments:

- *"I think that human research and expertise will always play more important role in the identification of deep metal enrichments than AI and ML. However, the latter two factors will make the process more precise."*
- *"The golden age of ML and AI is coming and hopefully the exploration industry will realise its potential and use it for their own purposes. I think this could bring a significant breakthrough for interpretation of noisy data, of weak signals covered by noise. I would also highlight the use of statistical tools when looking for deep metal enrichments."*

- *"Necessary to undertake significant work to improve the technology of confident drilling at depths 6-10 km. Without any actual field material, any predictive models will be predictable."*

## 5.8. Statement on Investors (8/12)

***→ Mining investors are the main drivers for CHPM projects development.***




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 3,0 | 4,0 | 4,0 | Mode |
| 2,7 | 3,3 | 3,4 | 2,8 | Average |

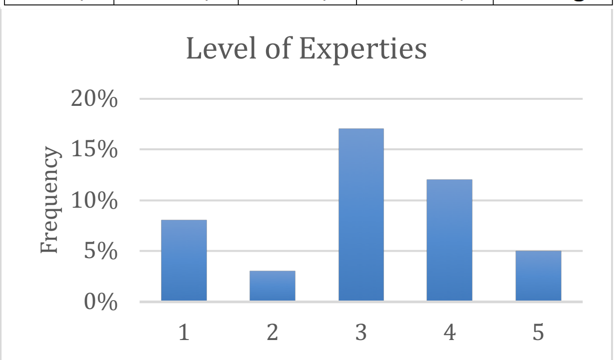


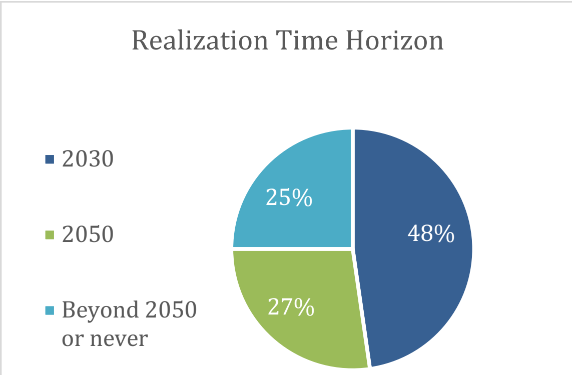

*Figure 29: Statistics from the Delphi round 1, statement 8/12*

Some comments identified facts about mining that were relevant to the statement such as that the mining sector has more capital to invest and it is looking for cleaner ways of operating (such as using renewable energy sources). Some references were also made to the importance of state actors - and public funding. The most commonly raised issue was that the public/government support will still be highly required - through e.g. new funding, risk sharing schemes.

Highlights of comments:

- *"For electricity generation mining sector will be the driver, for the valorization of heat (under 120°C) the drivers should be both mining sector and potential heat consumers"*
- *"My experience has indicated that the political decision counts as much"*
- *"If the mining sector identifies CHPM technology as a PR tool, to build a greener image, they can be real drivers here."*

In the second round, the compounded judgement of 75% of the participants is that by 2050 this statement will be true (Figure 30). Consensus can be observed that mining can play a role as one if not the main driver of CHPM.



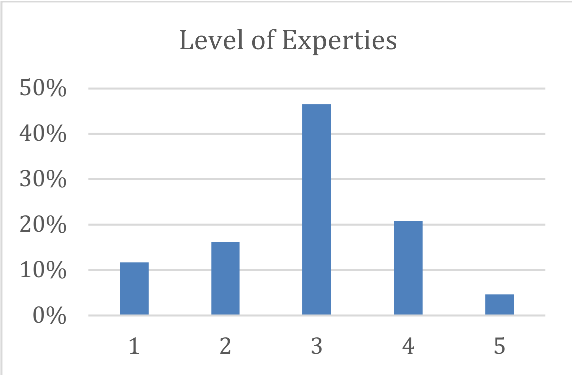




*Figure 30: Statistics from the Delphi round 2, statement 8/12*

Factors considered were that mining operations are going deeper, increasingly looking for renewable sources of energy. On the other hand, mining companies are primarily raw materials producers and no additional big business pivoting could be expected from their mainstream activities.

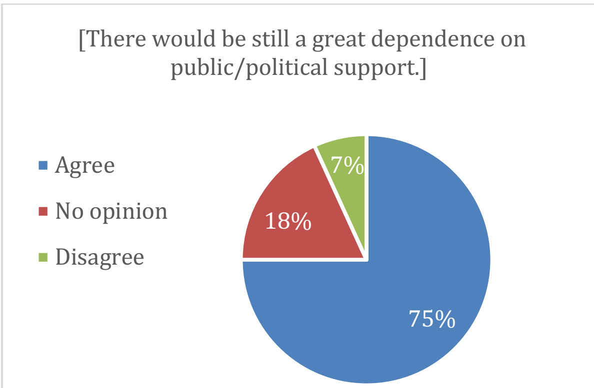



*Figure 31: agreement on emerging issues, round 2, statement 8/12*

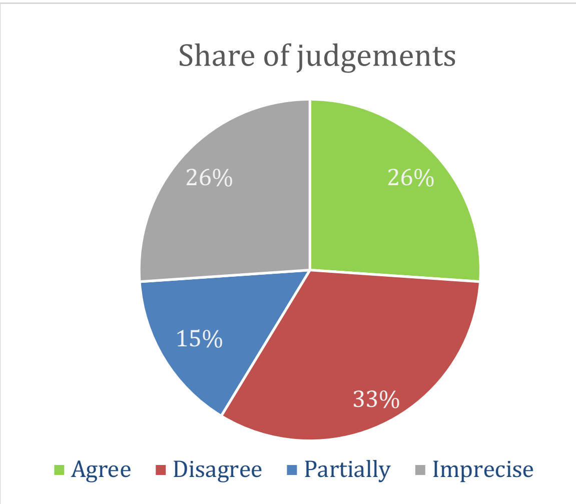
As a summary, 1) public funding might still be a key aspect, 2) CHPM has to prove better than other alternatives, 3) Shorter-term return view for mining may be a barrier, 4) Socio-political aspects & communication will be very important.

Highlights of comments:

- *"Yes, this makes sense. If the technology is feasible money can be made, possibly much more money then with just geothermal energy. It would be interesting to see various revenue scenarios and also to understand how these would change in time."*
- *"There are many alternatives to CHPM (nuclear, biological mining etc) with their respective lobby groups. Public/political support is just as critical as in any other fields for CHPM to gain momentum."*
- *"I think the driver is a political one. Not an economical one, simply because investors run away from risk…"*
- *"The mining industry could make use of the technology for the deeper levels of operating mines."*
- *"As mining investors have fewer opportunities in traditional mining I expect they will be interested in new technology for obtaining metals"*

## 5.9. Statement on Drilling depth (9/12)

***→ Mining companies routinely drill for mineral exploration down to great depths relevant for CHPM technology.***




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 4,0 | 3,0 | 3,0 | Mode |
| 3,1 | 3,7 | 3,7 | 2,8 | Average |

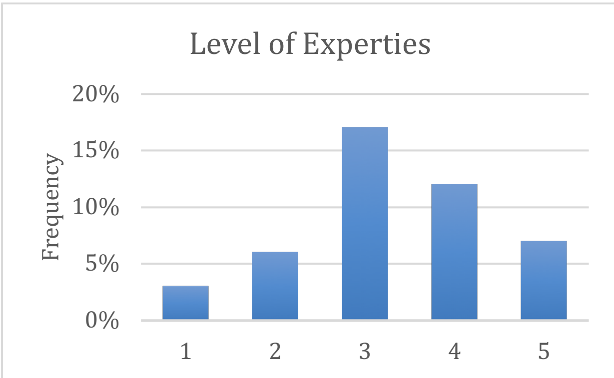



*Figure 32: Statistics from the Delphi round 1, statement 9/12*

The level of disagreement was relatively high - the term "routinely" was noted a few times as unlikely and was deemed as too ambitious.

Highlights of comments:

- *"Problem of handling the radioactivity of the circulating brines, including the contaminated technical installations of the primary circle"*
- *"Need significant cost reduction for exploration drilling for here. Also drilling time shall decrease, safety increase, drill rig size/footprint decrease, etc"*
- *"This practice might locally be representative in case of bigger metal prospects though, where commodity prices are higher."*
- *"At this stage, it is necessary to improve the technology of inclined and horizontal drilling for CHPM project"*
- *"Mining sector is drilling usually slim holes which are not suitable for geothermal exploration and exploitation"*
- *"Improvements in drilling speed, reduction in drilling costs, and increasing value being placed on data"*

**New statement: "Mining companies gained solid experience in drilling down to 6 km depths by 2050."**

More than half of the respondents (54%) believe the statement will only be true by 2050. Only 23% believe it won't turn true in the given time horizons (Figure 33)

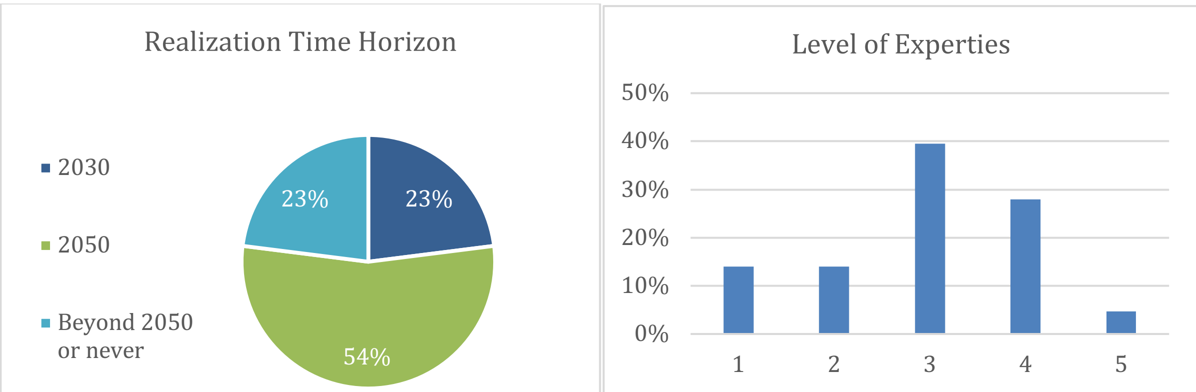



*Figure 33: Statistics from the Delphi round 2, statement 9/12*

Although it is recognised that such statement can be true, it is pointed out that different drilling techniques and approaches are used for mineral and geothermal drilling, with Oil & Gas providing good benchmarks, not the mining industry. Further advancements in the quality and durability of the materials, new technologies in the tilting and horizontal drilling capacities were also important issues. Sealing and cementing quality are also important for the future.

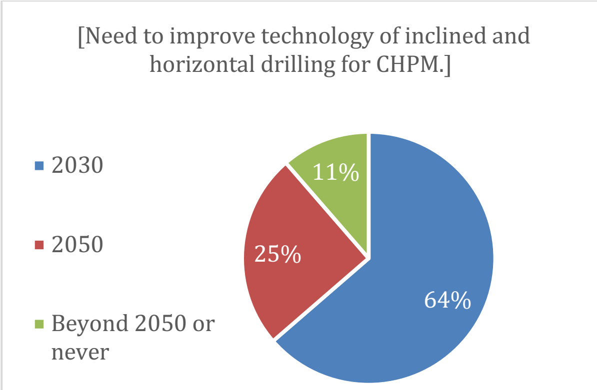



*Figure 34: Agreement on emerging issues, round 2, statement 9/12*

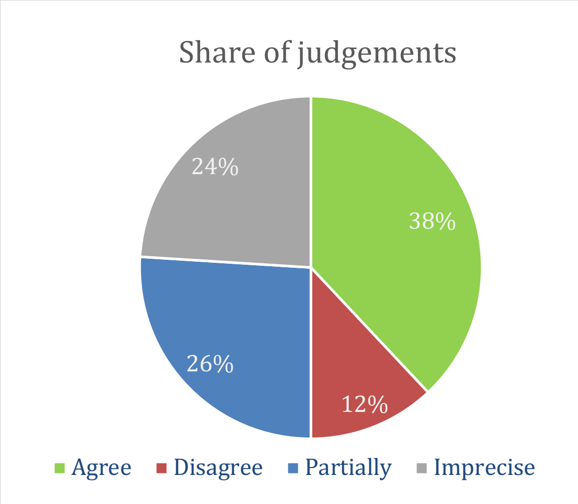
Highlights of comments:

- *"Drilling technologies and methods used in mineral exploration (up to 1500m depth) have nothing to do with geothermal drilling. The benchmark here is O&G drilling methods. And these can be easily transferable / adapted to geothermal."*
- *"Look at the oil and gas industry, they are drilling very deep, inclined and directed routinely"*
- *"Drilling at depths over 6 km requires an urgent solution to a number of technological problems: the quality and environmental cleanliness of the drilling mud, the quality and durability of the metal (or other new materials?) When working in extreme conditions of temperature and pressure, high quality sealing and cementation of the columns. The technology of tilting and horizontal drilling is one of the ways of complex development of deposits."*

### 5.10. Statement on Public Acceptance (10/12)

***→ The public is against Enhanced Geothermal Systems due to concerns about environmental impacts (e.g., induced seismicity, emissions, long term effects, etc.).***

This statement was formulated in a provocative and negative way to encourage commenting, however it received relatively high level of agreement (Figure 35). Some comment brought up the relation with the local context as an important issue. Necessity of informing and educating the public was also mentioned frequently.




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 4,0 | 3,0 | 2,0 | Mode |
| 3,3 | 2,8 | 3,8 | 3,0 | Average |

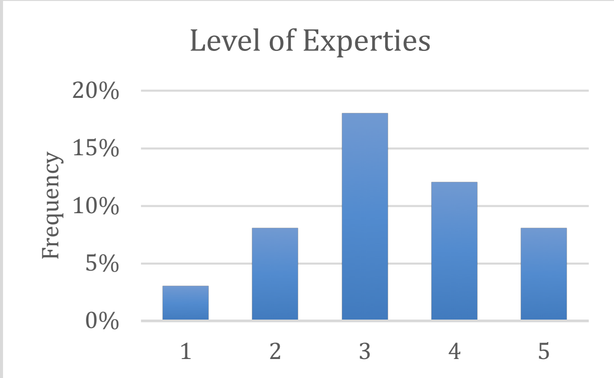



*Figure 35: Statistics from the Delphi round 1, statement 10/12*

Highlights of first round comments:

- *"Social media would be a powerful instrument, in both ways"*
- *"If the support is not there by the public in the medium term we will not see EGS as a popular and safe way to extract geothermal energy in the long term (2050)"*
- *"Already well-functioning geothermal plants in Germany that are accepted."*
- *"I am aware studies are being performed on public perception of both enhanced geothermal systems and induced seismicity. These studies will be key to developing strategies to reduce public anxiety around EGS development in the future."*
- *"Small, but very active opponent groups dominate unfortunately the discussions"*

In the second round, the participants agreed that it is very important to gain the public trust from the very beginning. Clear demonstration of successful applications is very important, and then social political support will follow. However, a NIMBY – "Not In My Back Yard" effect can be expected, even if the people understand the technology. The use of media, communication and involvement of the public could also be a powerful tool. There was no timeline included in this statement, only level of expertise (Figure 36)

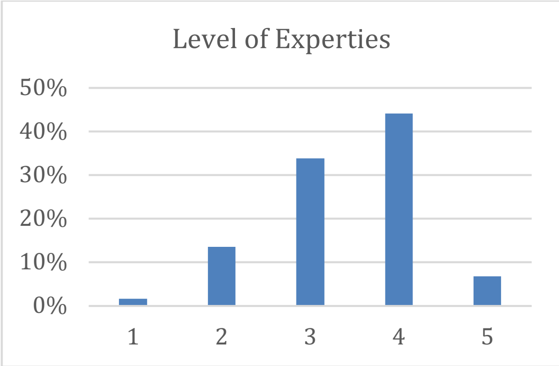



*Figure 36: Statistics from the Delphi round 2, statement 10/12*

During the first round there has been 3 topics identified (Figure 37), as emerging issues, that was included in the second round for voting, about the regional dependence of SLO, environmental activist, and the formation of public perception.

Issue 1: Social acceptance will be very region dependent.

- *"Public awareness and acceptance only achievable via education."*

Issue 2: As CHPM begins to raise interest, it will become a target of environmental activists.

- *"It would be important to build up a positive image from the very beginning."*

Issue 3: Successful or unsuccessful experiences of related technologies will play a key role on the public's perception on EGS.

- *"EGS already has some positive experience in public acceptance e.g. France and Germany EGS power plants. But also very negative experience which shut down a whole project (e.g. Basel, Switzerland) or nowadays Pohang in South Korea is also struggling due to (quite significant) induced seismicity. The positive/negative examples of EGS/CHPM will drive public acceptance or non-acceptance."*
- *"The key is how well the environmental impacts of the early projects are handled. If they are successfully avoided or mitigated, public acceptance will probably follow. A few poorly handled early projects could, however, quickly sour the public on the technology."*

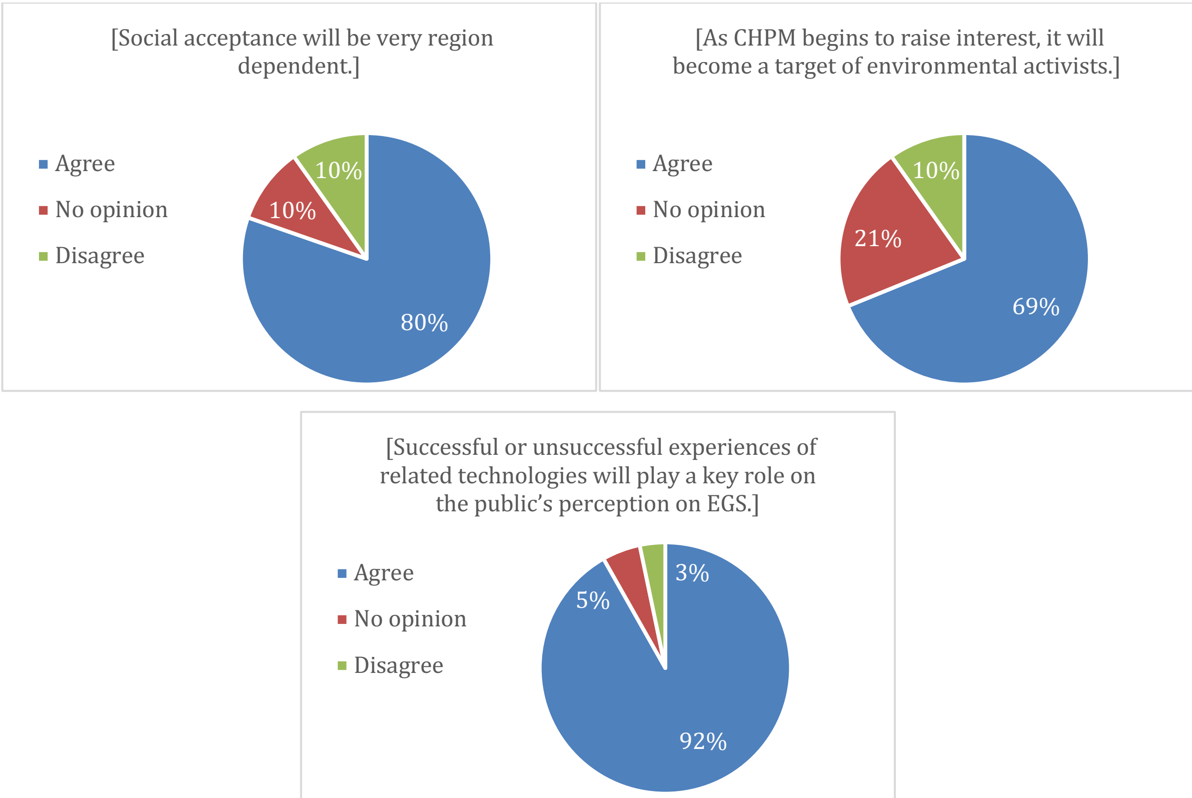


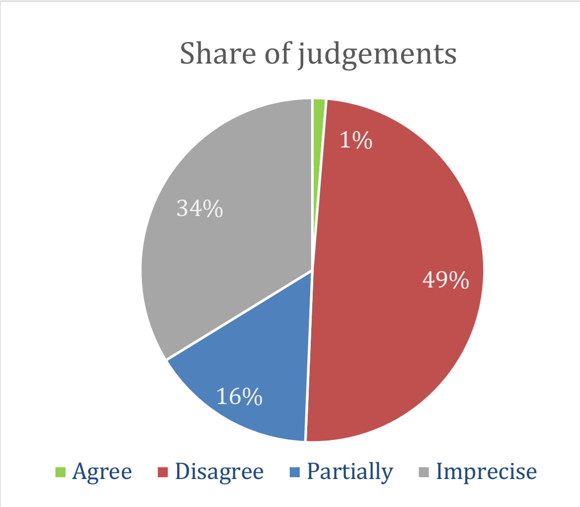

*Figure 37: Agreement on emerging issues, round 2, statement 10/12*

Further emerging issues identified related to Public Acceptance:

- *"Need for clear evidence"*
- *"Previous related positive/negative examples will drive public acceptance for EGS/CHPM"*
- *"Best way is to deal with them face-to-face. Being forthright and honest makes the job easier"*
- *"Communication will be key in these operations."*
- *"Early and broad stakeholder engagement is normally the key"*
- *"There will always be a NIMBY effect 'Not in my backyard'"*
- *"Implementation is a key aspect under scrutiny of public acceptance"*
- *"The word "fracking" makes it negative. It is nearly impossible to talk to media or political persons as a fact oriented basis. Politicians follow the media dominated public opinion (populism)."*
- *"Every village, municipality or a hospital could drill own deep well and heat all the area. There are some researches in Germany "Erdwärmesonde" about it and this will be future geothermal power. Public will beg to use this geothermal system. "*

### 5.11. Statement on Revenue Streams (11/12)

**→ *Expected revenue streams from metal recovery completely eliminate drilling risks associated with conventional geothermal development.***




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 3,0 | 4,0 | 1,0 | Mode |
| 3,0 | 3,3 | 3,2 | 2,4 | Average |

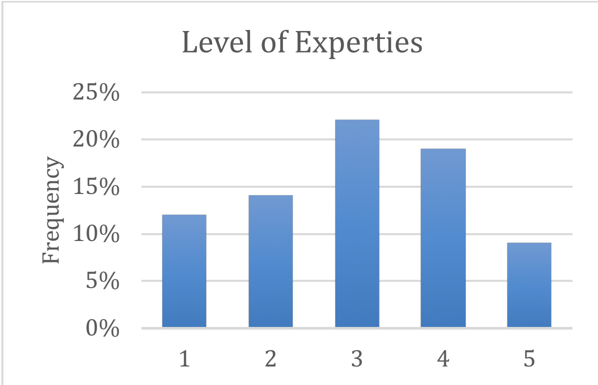



*Figure 38: Statistics from the Delphi round 1, statement 11/12*

A relative unease with the formulation of the statement drawing attention to the difference between “Technical Risk” and “Financial Risk” led to a high level of disagreement with the statement. The most common issues raised were 1) this will be very site-specific, 2) there will always be risks, 3) tendency to consider lower concentration deposits.

Highlights of comments:

- *“Viability of this approach would require a new synergy between the geothermal, mineral and state sectors to allow for separate developments to progress simultaneously using a single infrastructure”*
- *“The change in market value overtime should be considered.”*
- *“It will mainly depend on the metal price”*
- *“Ultimately, the quality of the exploration data is decisive.”*
- *“A good example is the appearance of shale gas in North America which induced a significant reduction of the gas price since 2010”*

In the second round, Half of the respondents believe that this statement won’t become true by 2050 or beyond (Figure 39).

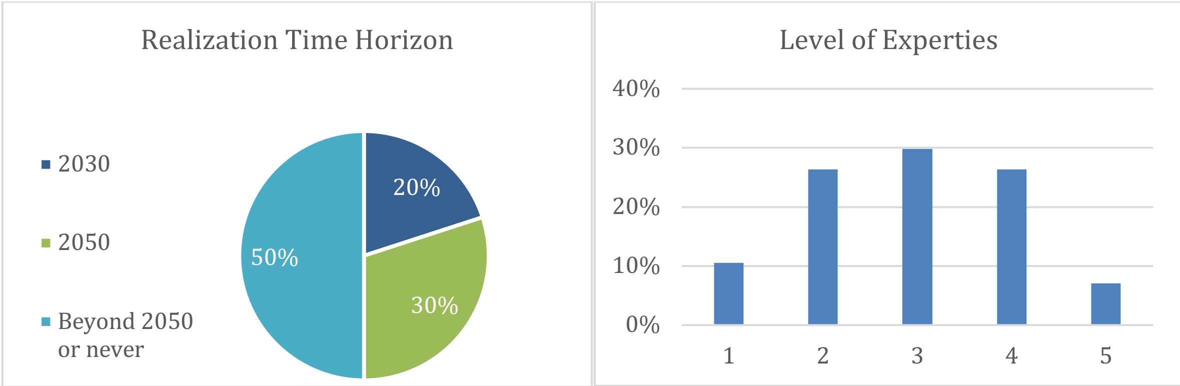



*Figure 39: Statistics from the Delphi round 2, statement 11/12*

Uncertainty related to metal production rates was the main source of scepticism over the statement.

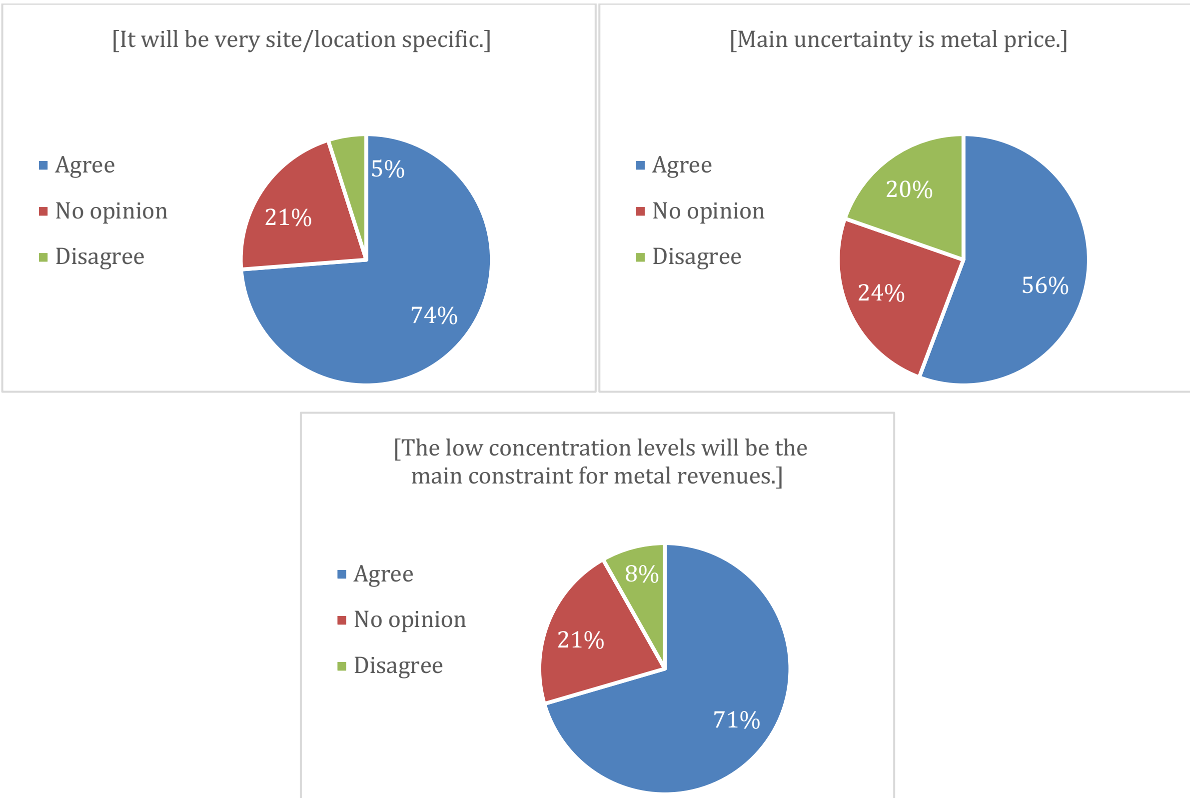



*Figure 40: Agreement on emerging issues, round 2, statement 11/12*

In summary, the level of a risk reduction will depend on the project, however risk mitigation remains an essential aspect. It is key to identify the financial contribution potential of metal recovery.

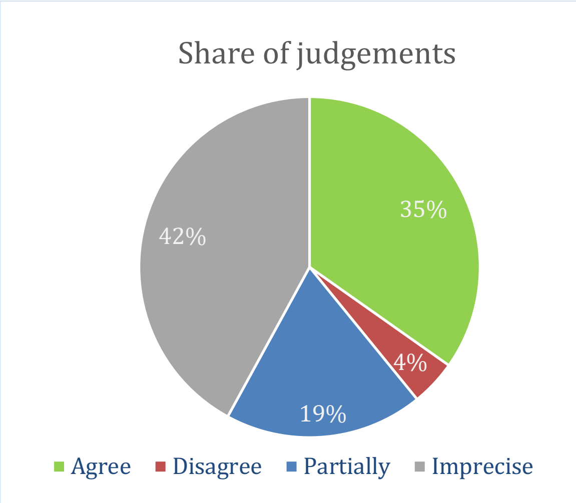
Highlights of comments:

- *"Many concurring techniques compete and for CHPM to raise to prominence this technique needs to be better than the others - risk mitigation is a key in this respect."*
- *"I don't think that the dissolved metal load will ever be so high as to generate so much revenue as to cover drilling costs. But it could be enough to swing the economics of heat recovery from loss-making to profit-making."*
- *"You should also focus on shallower developments only heat + metals, this would make this concept financially successful much sooner"*
- *"I think technical and financial risks are not, in this specific case, directly linked. The driver of CHPM technology is political, and not economic. And the technical risk is always there. More revenues won't affect this…"*
- *"In case where a portfolio approach is adopted, expected revenue streams from metal recovery significantly reduce the financial consequence of drilling hazard associated with conventional geothermal development.".*
- *Leach mining from highly concentrated ores will still only produce relatively low metal production rates at the surface. I suspect that the thermal energy will always provide the principal revenue stream from a CHPM project, with the additional value of metal production 'tipping the balance' in favour of otherwise economically marginal heat mining projects. Metal production will never fully justify (rather than "completely eliminate") the drilling risk on its own, but only as a component of the full economic equation for the project.*

### 5.12. Statement on Market Penetration (12/12)

***→ CHPM technology is highly successful but only reaches moderate market penetration due to the low number of suitable formations where it could be developed.***

Experts said that extreme depth is uncharted yet, therefore it is difficult to confirm if this statement is true or not. CHPM could become a side project at deep levels of known and exploited deposits. It was also acknowledged that the real bottleneck of CHPM technology is not the availability of suitable formations. It was commonly raised that it will be very site-specific.




| Agree | Disagree | Partially | Imprecise | |
|---|---|---|---|---|
| 3,0 | 3,0 | 3,0 | 1,0 | Mode |
| 3,3 | 3,3 | 3,1 | 2,6 | Average |

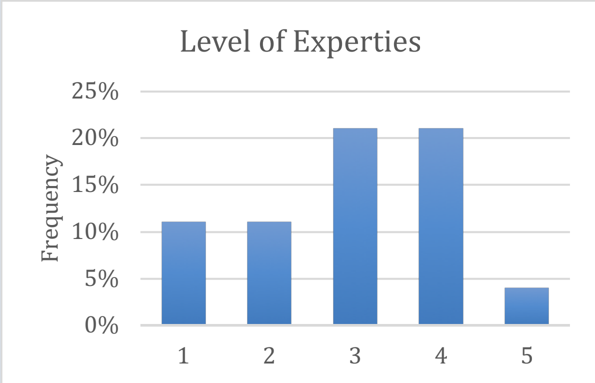
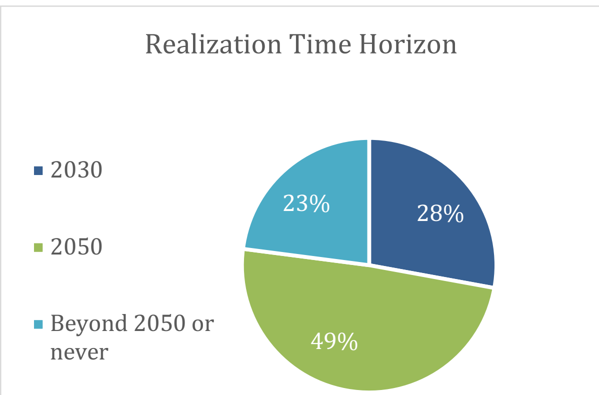



*Figure 41: Statistics from the Delphi round 1, statement 12/12*

Highlights of comments:

- *“The potential of deep geological formations is not widely known, we cannot say that the applicability of the technology is limited”*
- *“Without the increase in viability of deeper resources from both sectors, the technology will be limited to high gradient formations.”*
- *“Formations suitable are those where permeability can "easily" be increased, and these are limited”*
- *“I see a high market potential for Li and REE with a moderate market penetration, generated mostly as side effects of hydrothermal projects initially planned without metal extraction but having recovered high concentrations within the produced brine by accident”*

In the second round, half of respondents (49%) believe this statement will be true only by 2050 (Figure 42).



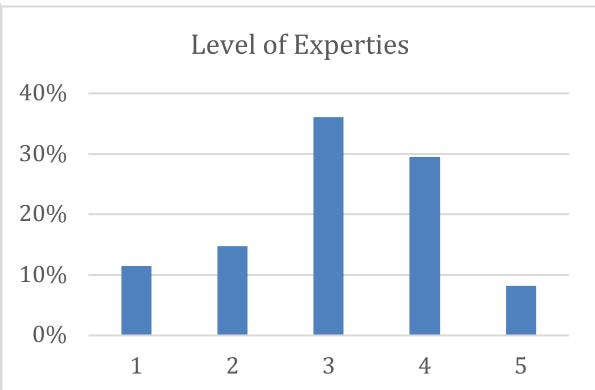



*Figure 42: Statistics from the Delphi round 2, statement 12/12*

In general, it is said that the market penetration is dependent on the market structure and overall constrained by the lower number of potential sites and production rates that can be achieved.

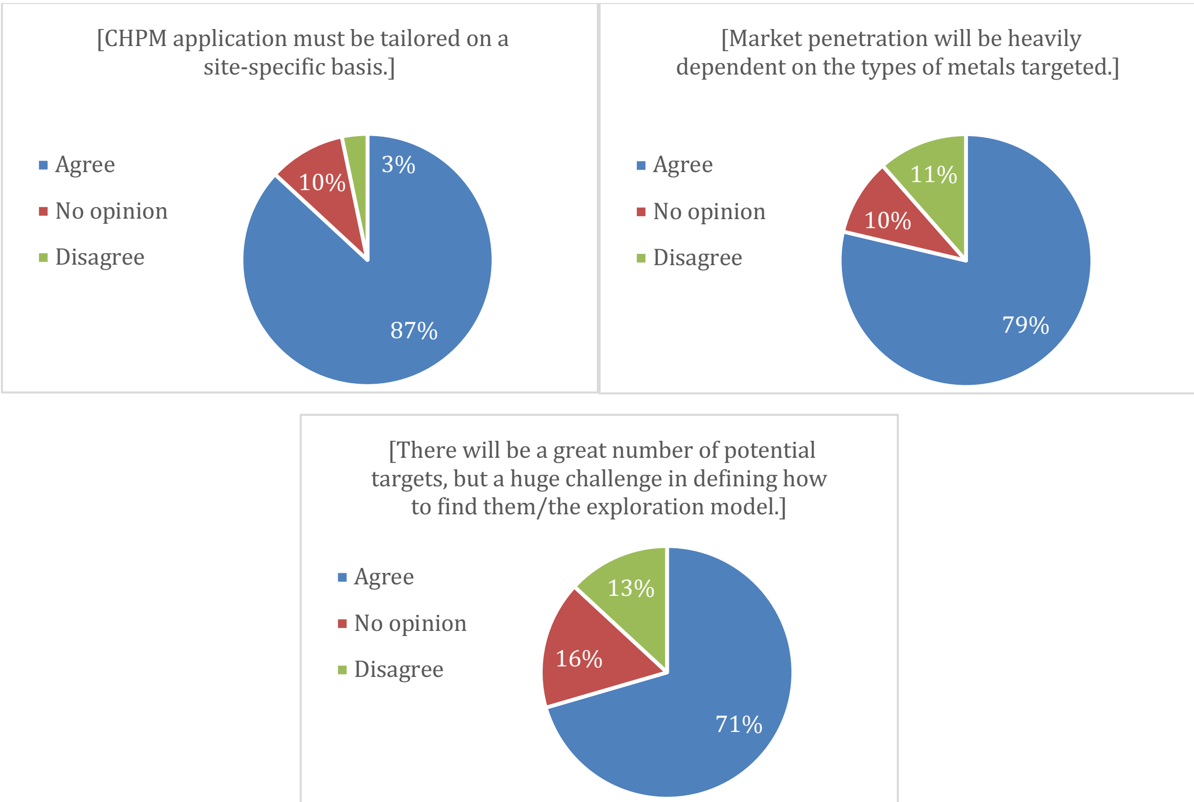



*Figure 43: Agreement on emerging issues, round 2, statement 12/12*

As a summary of emerging issues raised, there may be only a handful of known promising sites, and only a limited number of metals would have commercial potential.

Highlights of comments:

- *"This is a likely scenario. I think that perhaps there are only a handful of sites that can be developed in an economically/technologically feasible manner in Europe - at least within the investigated timeframes. It could be a good idea to also explore less ambitious scenarios (such as aiming for heat and metals removals only and aiming for shallower depths)."*

- *"It is not just the rock formation, but also the nature of the deep (geothermal) groundwaters within it, as saline waters may be able to carry more metals than more dilute waters."*
- *"A lot will depend on the accuracy (and capacity) of geophysical methods. But the market penetration depends mainly on socio-political factors. The price of metals, a trade war or a conflict can trigger massive investments into alternative solutions such as the one provided by CHPM."*
- *"There should be plenty of sites available and awaiting exploration. The bottleneck is rather interest/financing."*

### 5.13. Statement on Mars (13/12)

***→ The first permanent settlement on Mars uses CHPM technology to satisfy its needs for energy and metals.***

Mars has a single hotspot region, Tharsis province that is likely to have massive igneous and hydrothermal ore deposits combined with high geothermal gradient. If the base is there then this could be feasible.

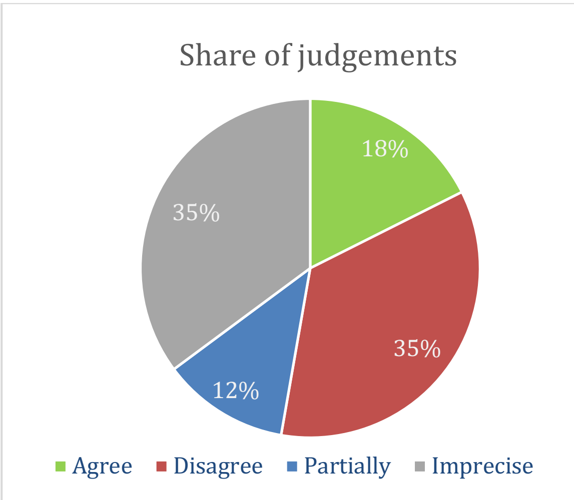



*Figure 44: Statistics from the Delphi round 1, statement 13/12*

The issues came up were related to the local geothermal gradient, permafrost, water availability, "un-tested" technology. On the other hand, NASA's InSight mission successfully landed on Mars, with contribution from ETH Zurich researchers on sensor's data acquisition and control electronic[13], acquiring seismic and heat flow measurements, so this information will be soon available. It was also pointed out the in a "virgin" environment, resources lie relatively in easy reach of the surface, and as far as energy concerned, solar power seems to be the practical solution. This topic was a bonus statement, beyond the immediate scope of the CHPM2030 project. Nevertheless, it was interesting to test the participants with such a "wild" idea for the future of CHPM technology. Time horizon was intentionally not indicated here.

Highlights of comments from the first and second rounds:

- *,,Depends on geothermal gradient, water availability."*
- *,,Why not! Currently researchers from ETH Zurich are sending the first Mars seismometer and a heat flow measurement device on a satellite to Mars."*
- *,,Unlikely. The apparent low thermal gradient and deep permafrost on Mars would necessitate drilling a long way down to reach free water."*
- *"(...)In a virgin environment it is likely that mineral resources lie within easy reach of the surface"*
- *"I think that this technology is very much suitable for the Mars region you mentioned and from a metals extraction point of view this may be the fastest, cheapest and most efficient way to produce metals locally. Free energy would be a bonus. I think you should explore this dimension further and approach ESA with the concept."*
- *"Thinking about Mars is a pure utopia."*
- *"There are too many unknown variables, related to both CHPM technology and the potential on Mars."*

## 6. The Visioning Process

By the end of Task 6.1, an overall CHPM vision was defined in the relevant areas. These relevant areas and their related specific issues were delivered from the Horizon Scanning exercise and the Delphi survey. 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

[13] http://www.insight.ethz.ch/en/home/

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[14]) and 2050 (commercial applications readiness level, TRL8-9[15]). In comparison (Figure 45), the Vision defines "Where to go?", with tangible targets to be achieved, and the Roadmaps outlines "How to get there?", with actions and timeline for implementation. Therefore, the goal of the Vision workshop (Las Palmas, 04.12.2018) was to create a shared vision, clear picture, description about where we would like to be by 2030/2050 and set tangible/measurable targets. This was a forward-thinking process: starting from baseline today towards the desired future. On the other hand, the goal of the subsequent Roadmapping workshop (Las Palmas, 07.03.2019) was to create a strategic plan, exploring how to arrive to the desired vision. This was a back-casting process: starting from the desired future, and investigate what are the steps to be taken to arrive to that future, with critical milestones.


*Figure 45: Vision and Roadmap word clouds*

The CHPM2030 Visioning process brought together 20 Experts (Figure 46) from both the mineral and geothermal sectors, industry, academia, research centres, and have taken on the challenge of setting targets to the already identified targets. The visioning exercise connected the previous foresight results, Horizon Scanning and Delphi survey with the Roadmap, with

[14] TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 – system prototype demonstration in operational environment
[15] TRL 8 – system complete and qualified
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

the creation of targets, considering the influence of the outcomes on the technology future research.

*Figure 46: Visioning workshop participants (Las Palmas, 04.12.2018)*

The Visioning workshop begun with introductory presentations (Tamas Madarasz: CHPM state-of-the-art, Tamas Miklovicz: WP6 context and Marco Konrat: Visioning methodology). After the presentations, the main exercise was the group discussion of the identified topics, as well as about requirements vs. achievability and targets that must be achieved before CHPM technology can reach pilot level (TRL 6-7) by 2030 and full scale (TRL 8-9) by 2050. The different topics were organised to the following groups, with two group discussion running parallel:

- Exploration: geophysics, ML & AI, drilling depths,
- Market: mining investors, revenue streams, market penetration,
- Development: drilling risk, reservoir stimulation, public acceptance,
- Operation: metal mobilisation, geochemical processes, corrosion.

Each subtopic included several issues that had emerged during the Delphi survey. The full list of issues was sent to the participants one week prior, with some background information about the Delphi results and visioning exercise. This was not an exhaustive list, and the participants added new ones or removed others during the group work (Figure 47). The aim of the group work was set measurable targets at each relevant issue for 2030 and/or 2050 (eg. reduce drilling cost by 2030 with 30%).

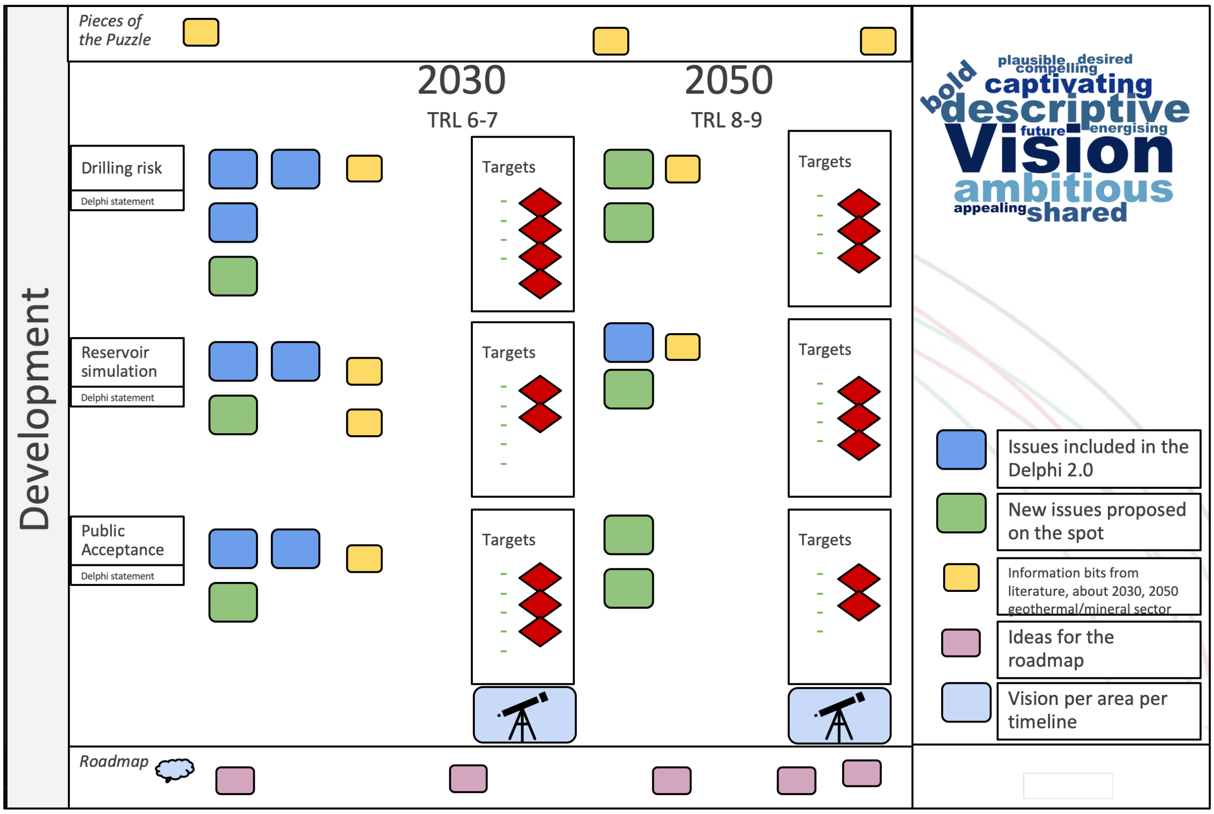



*Figure 47: Canvas design for the visioning exercise, group "Development"*

The sum of the targets is the vision for the given area related to the CHPM technology application (Figure 48). The targets are 'SMART' – Specific, Measurable, Attainable, Realistic and Time-based goals. During the exercise, the participants were reminded that it is not possible to cover all aspects, but it is possible to cover the most important ones, therefore priorities were set up. The last session was about consensus building. For this, the team brought all group visions together (per area, per time horizon) and created a shared vision for 2030 and 2050.

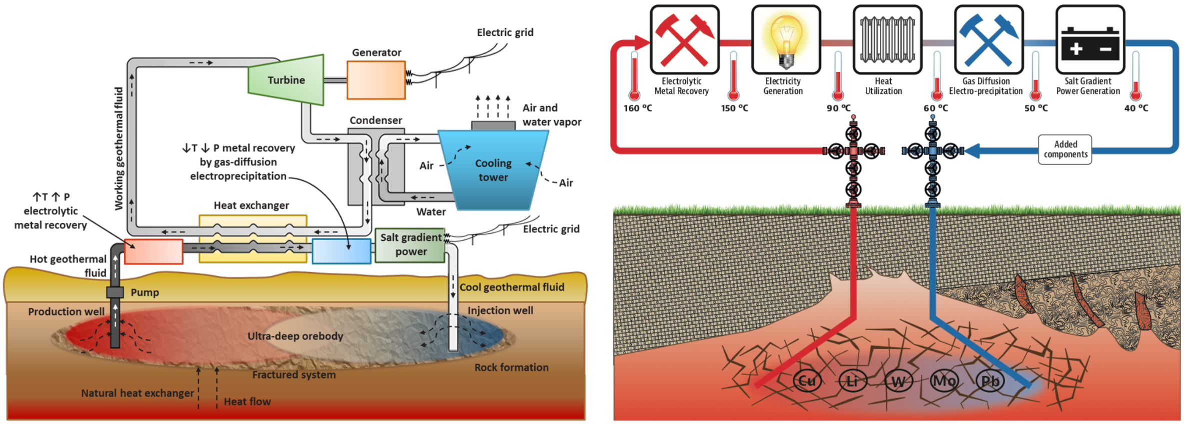



*Figure 48: The CHPM schematics (©CHPM2030 project)*

After the workshop LPRC processed the input and formulated a short vision description for each of the areas together with defined targets for 2030 and 2050 (Figure 49). The CHPM 2030 and 2050 roadmaps will be based on this vision and will outline actions

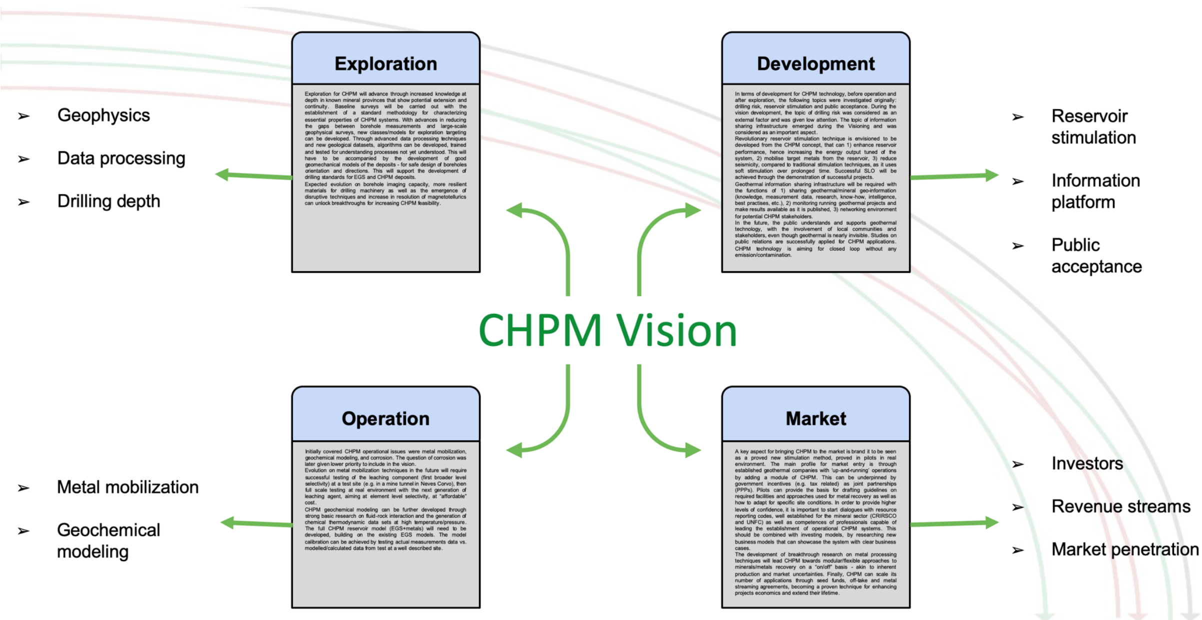



Figure 49: Overall CHPM Vision picture after the consensus building exercise and post processing (see the description of the areas in the following chapters)

## 6.1. Exploration

**Description:** Exploration for CHPM will advance through increased knowledge at depth in known mineral provinces that show potential extension and continuity. Baseline surveys will be carried out with the establishment of a standard methodology for characterizing essential properties of the CHPM systems. With advances in reducing the gaps between borehole measurements and large-scale geophysical surveys, new classes/models for exploration targeting can be developed. Through advanced data processing techniques and new geological datasets, algorithms can be developed, trained and tested for understanding processes not yet understood. This will have to be accompanied by the development of good geomechanical models of the deposits - for safe design of boreholes orientation and directions. This will support the development of drilling standards for EGS and exploration of mineral deposits suitable for CHPM technology.

Expected evolution on borehole imaging capacity, more resilient materials for drilling machinery as well as the emergence of disruptive techniques and increase in resolution of magnetotellurics can unlock breakthroughs for increasing CHPM feasibility

1) **Geophysics**

**Targets 2030:**

- Models of mineralisation that can have deep roots/be extended into depth - extrapolating current knowledge on known deposit models.
- Baseline surveys.
- Establish standard methodology for characterization of essential properties
- Reduce the gap between borehole measurements and large-scale geophysical survey
- Generating new classes/models for exploration targeting

**Targets 2050**:

- Borehole geophysical imaging capacity - for new data sets
- Increase resolution of magnetotellurics

2) **Data Processing (ML, AI..)**

**Targets 2030:**

- train and evolve algorithms for specific trials (pilots)
- Deep geological test sites - provide datasets for algorithms to be trained at

**Targets 2050**:

- developed data processing tools trained and tested - machine learning/AI algorithms used as data processors do understand processes yet not understood.

3) **Drilling Depths**

**Targets 2030:**

- Good geomechanical models of the deposits - safe design of boreholes orientations and directions, monitoring foliation

- Monitor emerging technologies such as contactless drilling (plasma/electro-impulse), laser technology for fracture enhancement and mudhammer
- Stimulate development of a drilling standard for the Geothermal sector

**Targets 2050**:

- drilling costs will continue to reduce with the development of adaptable/resilient materials, which should be researched for particular deep geothermal conditions.
- Drilling for CHPM with coring capacity e.g. DTH hammer
- Consideration on extra well (triplet) - remediation needs

### 6.2. Development

**Description:** In terms of development for CHPM technology, activities necessary to start up a successful CHPM operation, the following topics were considered originally: drilling risk, reservoir stimulation and public acceptance. During the group work the topic of drilling risk was considered as an external factor and was given low attention. The topic of information sharing infrastructure emerged during the discussion and the group considered it as important aspect to be included in the vision.

Revolutionary reservoir stimulation technique has been evolved from CHPM concept, that can 1) enhance reservoir performance, hence increasing the energy output tuned of the system, 2) mobilise target metals from the reservoir, 3) reduce seismicity, compared to traditional stimulation techniques, as it uses soft stimulation over prolonged time. Successful SLO is achieved through the demonstration of successful projects.

Geothermal information sharing infrastructure is in place with the functions of 1) sharing geothermal/mineral geo-information (knowledge, measured data, research, know-how, intelligence, etc.), available for new projects, 2) monitoring running geothermal projects , making results available as they are published, 3) networking environment for CHPM stakeholders.

The public understands and support geothermal technology, with the involvement from local communities and stakeholders, even though geothermal is nearly invisible. CHPM technology is aiming for closed loop without any emission/contamination. Studies on public relations are successfully applied for CHPM applications.

1) **Reservoir stimulation**

**Targets 2030:**

- Selective mobilisation of target metals.
- Reduced seismicity: de-risk reservoir stimulation, since CHPM uses mild leaching, soft stimulation, lower risk for seismic event.
- Safe technology demonstrated to the public.
- Successful SLO: through successful demonstration.

**Targets 2050**:

- Enhance reservoir performance and increase energy output of the system.
- Decrease ROI time by 10%.
- Better rate of success using CHPM stimulation than conventional.
- Proven and tested that CHPM create real added value for EGS projects.
- CHPM can be “subcontracted” to EGS projects for reservoir stimulation.

**2) Inheriting results from other projects as they become available**

**Targets 2030:**

- Platform for both geothermal mineral intelligence: sharing knowledge, data, research, best practises.
- Networking, technology transfer, monitoring ongoing projects.
- Make results available that feed into CHPM objectives.
- Covering the EU.

**Targets 2050**:

- the platform covers global scale.

**3) Public acceptance**

**Targets 2030:**

- Inheriting latest outcome from other projects running on public acceptance for CHPM purposes.
- Effective communication, involvement and awareness raising towards the local communities and stakeholders for geothermal solutions, including CHPM.
- Make geothermal visible for people, and explain processes, so they understand, public knowledge of geothermal energy, awareness.

**Targets 2050**:

- Closed loop for CHPM without emission/contamination.

### 6.3. Operation

Regarding operational issues at CHPM technology, the original overall topics were metal mobilization, geochemical modeling, and corrosion. During the discussions the topic on corrosion was given lower priority.

The research on metal mobilization in the future will require successful testing of the leaching component (broader level selectivity) at a test site (e.g. in a mine tunnel in Neves Corvo), then full scale testing at real environment with the next generation of leaching agent, aiming at element level selectivity, at "affordable" cost.

Geochemical modeling acquired strong basic research on fluid-rock interaction and chemical thermodynamic data sets are available, and full CHPM reservoir (EGS+metals) can be modelled, building on the extension of existing EGS models. The models are tested with comparing measurements data vs. calculated data from test at a well described site.

1) **Metal mobilisation**

**Targets 2030:**

- Running a "half-system" for leaching component at test site (e.g. between mine tunnels in Neves Corvo).
- Broader selectivity (e.g. group of elements, target vs. non-target metals).
- New chemical agents for mobilization and solution, nanoparticles, physical sorbents.

**Targets 2050**:

- Testing the next generation leaching agent at a large scale.
- Element level selectivity.
- "Acceptable" cost of leaching fluid.
- Real field test with site tailored leaching agents.

2) **Modelling geochemical processes**

**Targets 2030:**

- Testing at a well described site: flow, thermal and pressure gradients, solution precipitation, and compare measured data with modelled results.
- Add mineral component to existing EGS models.
- Availability of new chemical thermodynamic data sets.
- strong basic research on geochemical and fluid rock interaction.

**Targets 2050**:

- Develop full EGS reservoir + metal enrichment simulation models.

## 6.4. Market

**Description:** A key aspect for bringing CHPM to the market is brand it to be seen as a proved new stimulation method, proved in pilots in real environment. The main profile for market entry is through established geothermal companies with 'up-and-running' operations by adding a module of CHPM. This can be underpinned by government incentives (e.g. tax related) as joint partnerships (PPPs). Pilots can provide the basis for drafting guidelines on required facilities and approaches used for metal recovery as well as how to adapt for specific site conditions. In order to provide higher levels of confidence, it is important to start dialogues with resource reporting codes, well established for the mineral sector (CRIRSCO and UNFC) as well as competences of professionals capable of leading the establishment of operational CHPM systems. This should be combined with investing models, by researching new business models that can showcase the system with clear business cases.

The development of breakthrough research on metal processing techniques will lead CHPM towards modular/flexible approaches to minerals/metals recovery on a "on/off" basis - akin to inherent production and market uncertainties. Finally, CHPM can scale its number of applications through seed funds, off-take and metal streaming agreements, becoming a proven technique for enhancing projects economics and extend their lifetime.

**1) Investors for CHPM**

**Targets 2030:**

- Draft guidelines for reporting code in alignment with CRIRSCO and UNFC.
- Advance investing models - partnership between governments and industry (power+heat companies): set new business models to introduce the system in different business cases.
- Research incentives that could be set by governments (e.g. tax related) for making it more affordable.
- Main profile of early adopter: geothermal company with 'up-and-running' operations that could add a 'module' of CHPM.
- To be seen as a proved new stimulation method.

**Targets 2050**:

- Proved enhancement of existing projects.

- Modular/flexible response to metal recovery potential "on/off switch".
- Target seed funds.
- Establish competence for CHPM resources.

**2) Revenue Streams**

**Targets 2030:**

- Guidelines for defining the facilities and approaches used to recover metals - fine-tuned for site-specific conditions.
- Licensing procedures most likely in relation to heat and power generation as it follows where most of revenue is coming from.

**Targets 2050**:

- Work on a "take-what-you-get basis" - reduce uncertainties on how much metal can be recovered all of the time.
- Metal streaming, off-take agreements.
- 2050 Positive financial balance, the technology pays for itself.
- CHPM can offer new services for other EGS projects.

**3) Market Penetration**

**Targets 2050**:

- CHPM biggest contribution potential might come from its capacity to add value to projects and/or extend their lifetime.
- Not expected to have a consequential contribution on the supply base of metals in the next few decades.
- Plug-in ready for other EGS projects.

## 7. Conclusions and discussion

The CHPM technology is a low-TRL, novel concept that needs future-oriented thinking and further nurturing beyond the duration of the project. Task 6.1 mapped emerging issues and convergent technology areas using the synergetic combination of three foresight methods: Horizon Scanning, Delphi survey and a Visioning exercise. By mobilising external expertise these foresight tools provided new perspectives on what we can expect in important but uncertain areas. The foresight exercise delivered trends, new concepts and an array of convergent technologies that can support its implementation of CHPM by 2030/2050.

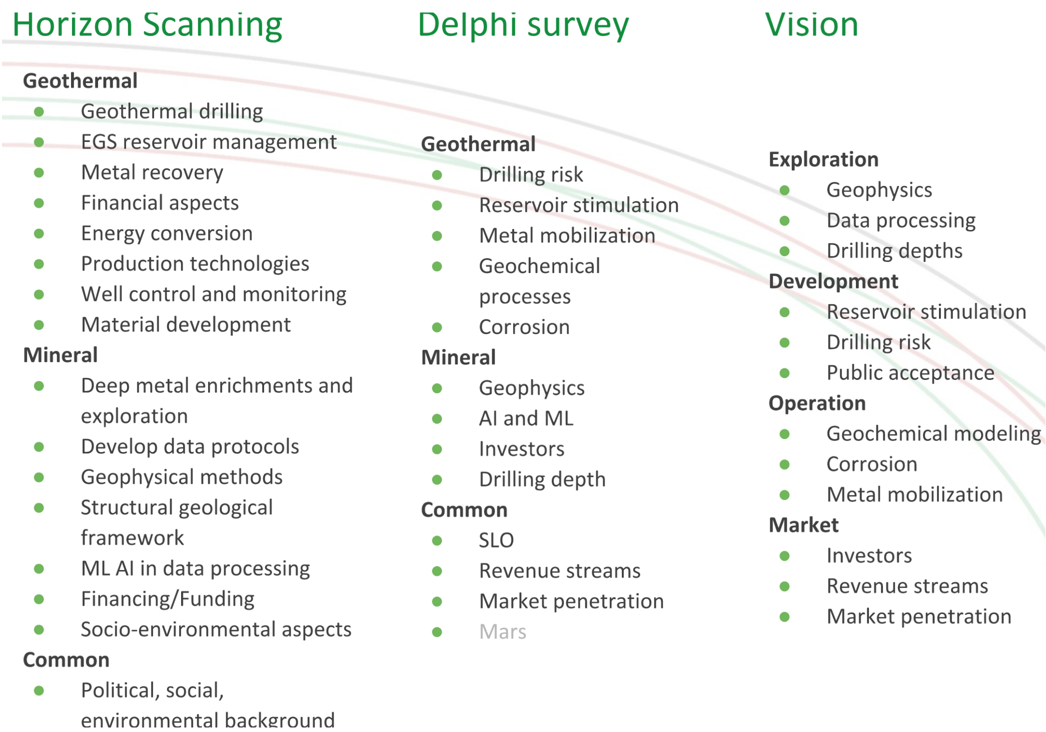



*Figure 50: Evolution of topics during the foresight exercise in T6.1*

The investigated topics and related issues continuously evolved during the implementation of the foresight exercise. The initial scoping started out from a broader range of topics from geothermal and minerals sectors, and merged, narrowed down to four CHPM system cycle: exploration, development, operation, market (Figure 50).

During the initial Horizon Scanning exercise, participants from the Consortium helped to frame the foresight process and the investigated issues. All participants were familiar with the CHPM technology concepts and were confident when defining issues. During the Delphi survey, external experts were mobilised, representing both the geothermal and mineral sectors, and for most of them, CHPM was a new concept. They brought up issues that hadn't been anticipated before. At the Visioning workshop there was a balance between Consortium partners and external experts, and they worked together in defining targets and objectives to be achieved in the future. Therefore, the type of input varied at different stage of the foresight process. However, at each stage, new issues came up and the participants reflected on previous issues, therefore there was a converging process on what is important for the future of CHPM. Table 2 summarises at emerging issues at Horizon Scanning, Delphi survey, Visioning processes. Each row represents a specific theme, and its evolution through technology foresight.

*Table 1. Emerging issues through the foresight process: Horizon Scanning, Delphi survey, Visioning - Theme: Exploration*

| Topic | Horizon Scanning | Delphi Survey | Visioning |
|---|---|---|---|
| Geophysics | Deep metal enrichments and exploration: focus on known mineralized/resources – extensions, low grade large tonnage, good understanding of hydrothermal alteration halo (diffuse metal distribution, understand zonation, properties, geometry, nature etc..). Regional extensional zones can also be potential areas. Usually elevated heat flow and multiple mineralization phases/overlapping.<br><br>Geophysical methods: improvements on resolution. | Massive, higher density sulphides and magnetic minerals would be easy to handle as opposed to disseminate and low grade material.<br><br>New geophysical techniques are combining Seismic, Satellite Remote Sensing, Gravity, Magnetic and Resistivity.<br><br>Appropriate geological models are required for geophysical investigation - new depths might require new models.<br><br>Exploration hardware will not improve as much as exploration software. | Models of mineralisation that can have deep roots/be extended into depth - extrapolating current knowledge on known deposit models.<br><br>New baseline surveys.<br><br>Establish standard methodology for characterization of essential properties.<br><br>Reduce the gap between borehole measurements and large-scale geophysical survey.<br><br>Generating new classes/models for exploration targeting.<br><br>Borehole geophysical imaging capacity for new data sets. |

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| | | | Increase resolution of magnetotellurics. |
| Data processing | Develop data protocols – collaboration industry/research institutions.<br><br>Structural geological framework: 4D models, flow circulation model, Hydrogeological model (Fluid flow model) – flow rate, direction.<br><br>Machine Learning, Artificial Intelligence and Data processing: Reinterpretation/Better interpretation of potential EGS systems. | The lack of availability of data at great depths might be an important barrier to apply AI and machine learning to aid prediction with high confidence.<br><br>New theories on bedrock development in different structural domains (or greater depths) will emerge.<br><br>Human interpretation and expertise will still be critical. | Train and evolve algorithms for specific trials (pilots).<br><br>Deep geological test sites - provide datasets for algorithms to be trained at.<br><br>Developed data processing tools trained and tested - machine learning/AI algorithms used as data processors do understand processes yet not understood. |
| Drilling depths | | *"Need significant cost reduction for exploration drilling for here. Also drilling time shall decrease, safety increase, drill rig size/footprint decrease, etc"*<br><br>*"Improvements in drilling speed, reduction in drilling costs, and increasing value being placed on data"* | Good geomechanical models of the deposits - safe design of boreholes orientations and directions, monitoring foliation.<br><br>Monitor emerging technologies such as contactless drilling (plasma/electro-impulse), laser technology for fracture enhancement and mudhammer. |

| | | | |
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| | | *"The benchmark here is O&G drilling methods. And these can be easily transferable / adapted to geothermal."*<br><br>Quality and durability of the materials; Sealing and cementation quality; Tilting and horizontal drilling capacities. | Stimulate development of a drilling standard for the Geothermal sector<br><br>Drilling costs will continue to reduce with the development of adaptable/resilient materials, which should be researched for particular deep geothermal conditions.<br><br>Drilling for CHPM with coring capacity e.g. DTH hammer,<br><br>Consideration on extra well (triplet) - remediation needs. |

*Table 2. Emerging issues through the foresight process: Horizon Scanning, Delphi survey, Visioning - Theme: Development*

| **Topic** | **Horizon Scanning** | **Delphi Survey** | **Visioning** |
|---|---|---|---|
| Reservoir stimulation | EGS reservoir management: geochemical dynamics, resource assessment (geothermal recovery factor, metal recovery factor, reuse of exhausted reservoirs), communication between injection and production | Bottlenecks are the political support, public resistance and potential environmental risks (e.g. induced seismicity). | Selective mobilisation of target metals.<br><br>Reduced seismicity: de-risk reservoir stimulation, since CHPM uses mild leaching, soft stimulation, lower risk for seismic event. |

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| | wells, selective leaching, reservoir stimulation, communication between industry and academics. | *"Control of environmental impact is key. If successful, public/political support".* | Safe technology demonstrated to the public.<br><br>Successful SLO: through successful demonstration.<br><br>Enhance reservoir performance and increase energy output of the system.<br><br>Decrease ROI time by 10%.<br><br>Better rate of success using CHPM stimulation than conventional.<br><br>Proven and tested that CHPM create real added value for EGS projects.<br><br>CHPM can be "subcontracted" to EGS projects for reservoir stimulation. |
| Information sharing platform | | Better data storage and management for drilling and subsurface data. | Platform for both geothermal mineral intelligence: sharing knowledge, data, research, best practises.<br><br>Networking, technology transfer, monitoring ongoing projects. |

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| | | | Make results available that feed into CHPM objectives.<br><br>The platform covers EU, then global scale. |
| Drilling risk | Geothermal drilling: exploration risk, drilling risk (yield of the well, permeability, drilling insurance, offshore operations), safety (high pressure reservoirs, incidents).<br><br>Well control and monitoring: advanced sensor development (electrochemical, optical, piezoelectric) resisting to high pressure/temperature. | Cooperation with the Oil & Gas industry is highly desirable: identify geothermal as an alternative business case, and adaptation of drilling technologies.<br><br>Development of new drilling techniques and materials (deep cementing; bit development and rig design for faster drilling and lower costs; high temperature (350 °C) proof equipment.<br><br>Better exploration workflows, insurance industry. | |
| Public acceptance | Political, social, environmental background: land use planning, public education and outreach, labour | Need to inform and educate the public to gain trust and build a positive image from the beginning. | Inheriting latest outcome from other projects running on public acceptance for CHPM purposes. |

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| | market attractiveness/competitiveness (quality training, value for the profession), legislation and regulatory framework, public acceptance, induced seismicity, communication. Improved public engagement: common language, education, outreach. | Clear demonstration of successful applications is very important, and then social political support will follow.<br><br>The use of media, communication and involvement of the public is a powerful tool.<br><br>*"The positive/negative examples of EGS/CHPM will drive public acceptance or non-acceptance."* | Effective communication, involvement and awareness raising towards the local communities and stakeholders for geothermal solutions, including CHPM.<br><br>Make geothermal visible for people, and explain processes, so they understand, public knowledge of geothermal energy, awareness.<br><br>Closed loop for CHPM without emission/contamination. |

*Table 3. Emerging issues through the foresight process: Horizon Scanning, Delphi survey, Visioning - Theme: Operation*

| **Topic** | **Horizon Scanning** | **Delphi Survey** | **Visioning** |
|---|---|---|---|
| Geochemical modeling | | Need advancement on computing power, reactive-transport code, obtaining reliable input, advancement in geochemical and fluid-rock interaction research in the geothermal space. | Testing at a well described site: flow, thermal and pressure gradients, solution precipitation, and compare measured data with modelled results. |

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|---|---|---|---|
| | | Availability of real input data about the reservoir fluid/rock chemistry, high-temperature chemical thermodynamic datasets. | Add mineral component to existing EGS models.<br><br>Availability of new chemical thermodynamic data sets.<br><br>strong basic research on geochemical and fluid rock interaction.<br><br>Develop full EGS reservoir + metal enrichment simulation models. |
| Corrosion | Production technologies: proppants, downhole pumps, scaling and corrosion, gases, Eh/pH conditions.<br><br>Material development: corrosion (cost, manufacturing), material selection. | Scaling is similarly, or more, important issue.<br><br>Cost of corrosion resistant advanced materials.<br><br>Metal-mineral interaction is an under-researched.<br><br>Use of cladding: covering the conventional steel pipe of production section with corrosive-resistant layer. | |

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|---|---|---|---|
| Metal mobilization<br><br>Metal recovery | Mobilization<br><br>Metal recovery: access to truly relevant metal containing brines, new strategies to increase selectivity, conceptual models for scaling up reactor design from lab to pilots, technology transfer from research to industry, element specific removal of interest metals at low concentration brines, alternative value chains (CO2 storage, CO2 working fluid), time factor of metal leaching. | Use chemical solvents or chelants to avoid early precipitation.<br><br>The potential environmental impact has to be closely investigated and to be proved safe.<br><br>Cost of operation. | Targets 2030:<br><br>Running a “half-system” for leaching component at test site (e.g. between mine tunnels in Neves Corvo).<br><br>Broader selectivity (e.g. group of elements, target vs. non-target metals).<br><br>New chemical agents for mobilization and solution, nanoparticles, physical sorbents.<br><br>Testing the next generation leaching agent at a large scale.<br><br>Element level selectivity.<br><br>“Acceptable” cost of leaching fluid.<br><br>Real field test with site tailored leaching agents. |

*Table 4. Emerging issues through the foresight process: Horizon Scanning, Delphi survey, Visioning - Theme: Market*

| **Topic** | **Horizon Scanning** | **Delphi Survey** | **Visioning** |
|---|---|---|---|
| Investors | Financial aspects: drilling insurance, competition with other energy sources (cheap solar, hydro, wind, biomass), investors interest, stockpiling.<br><br>Financing/Funding: e.g crowdfunding schemes, insurance schemes, tax rate – also for technology. Proximity with the demand is crucial and reduction of drilling costs (“drilling insurance”). New report standards might be needed - metal + heat resources/reserves. | Public/government support will still be highly required - through e.g. new funding, risk sharing schemes.<br><br>*“For electricity generation mining sector will be the driver, for the valorization of heat (under 120°C) the drivers should be both mining sector and potential heat consumers”*<br><br>Mining sector could play a role as one if not the main driver and investor of CHPM. | Draft guidelines for reporting code in alignment with CRIRSCO and UNFC.<br><br>Advance investing models - partnership between governments and industry (power+heat companies): set new business models to introduce the system in different business cases.<br><br>Research incentives that could be set by governments (e.g. tax related) for making it more affordable.<br><br>Main profile of early adopter: geothermal company with ‘up-and-running’ operations that could add a ‘module’ of CHPM.<br><br>To be seen as a proved new stimulation method. |

| | | | |
|---|---|---|---|
| | | | Proved enhancement of existing projects.<br><br>Modular/flexible response to metal recovery potential “on/off switch”.<br><br>Target seed funds.<br><br>Establish competence for CHPM resources. |
| Revenue streams | Socio-environmental aspects: Different fluids might mean different procedures. Also, Long-term monitoring capacity should be developed. | Its key to identify the financial contribution potential of metal recovery. | Guidelines for defining the facilities and approaches used to recover metals - fine-tuned for site-specific conditions.<br><br>Licensing procedures most likely in relation to heat and power generation as it follows where most of revenue is coming from.<br><br>Work on a “take-what-you-get basis” - reduce uncertainties on how much metal can be recovered all of the time.<br><br>Metal streaming, off-take agreements. |

| | | | |
|---|---|---|---|
| | | | 2050 Positive financial balance, the technology pays for itself.<br><br>CHPM can offer new services for other EGS projects. |
| Market penetration | | *"I see a high market potential for Li and REE with a moderate market penetration, generated mostly as side effects of hydrothermal projects initially planned without metal extraction but having recovered high concentrations within the produced brine by accident"*<br><br>The real bottleneck of CHPM technology is not the availability of suitable formations, but rather interest or financing. | CHPM biggest contribution potential might come from its capacity to add value to projects and/or extend their lifetime.<br><br>Not expected to have a consequential contribution on the supply base of metals in the next few decades.<br><br>Plug-in ready for other EGS projects. |

The next step in the forward-looking efforts of WP6 is the preparation of the roadmap itself. Technology roadmapping for CHPM will provide direct support for the early implementation of the pilots, whilst following up on the evolution of technology components. It is split into three actions or layers. One of the layers is going to represent 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 development in the future.

## References

Manuel Bustillo Revuelta, 2018: Mineral Resources - From exploration to sustainability assessment. Chapter 3. Springer DOI 10.1007/978-3-319-58760-8

Nami, P & Schellschmidt, Rüdiger & Schindler, M & Tischner, T. (0002). Chemical stimulation operations for reservoir development of the deep crystalline HDR/EGS system at Soultz-sous-Forêts (France). PROCEEDINGS.

David N. Bengston, 2013. Horizon scanning for environmental foresight: a review of issues and approaches. Gen. Tech. Rep. NRS-121. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 20 p

Andy Hines, David N. Bengston, Michael J. Dockry, and Adam Cowart: Setting Up a Horizon Scanning System: A U.S. Federal Agency Example. World Futures Review 2018, Vol. 10(2) 136–151. Link (accessed 29.04.2019): https://www.fs.fed.us/nrs/pubs/jrnl/2018/nrs_2018_hines-a_001.pdf

Kerstin Cuhls, Annelieke van der Giessen, Hannes Toivanen, 2015: Models of Horizon Scanning - How to integrate Horizon Scanning into European Research and Innovation Policies. Link (accessed 29.04.2019):

https://publications.europa.eu/en/publication-detail/-/publication/88ea0daa-0c3c-11e6-ba9a-01aa75ed71a1/language-en

Harold A. Linstone, Murray Turoff, 2002: The Delphi Method Techniques and Applications. Link (accessed 29.04.2019): https://web.njit.edu/~turoff/pubs/delphibook/delphibook.pdf

Conger, J. A., Benjamin, B., 1999: Building leaders: How successful companies develop the next generation. San Francisco: Jossey-Bass.

Tichy, N.M., Devanna M.A., 1986: The transformational leader. Hoboken, N.J: John Wiley & Sons.

Kotter J. 1982: The general managers. New York: The Free Press

Barge K. J., 1994: Leadership: Communication skills for organizations and groups. New York: St. Martin Press.

Baum J. R., Lock E. A. m Kirkpatrick S. A., 1998: A longitudinal study of the relation of vision and vision communication to venture growth in entrepreneurial firms. Journal of Applied Psychology, 83(1), 43-54.

Gallois, Cindy, Peta Ashworth, Joan Leach, and Kieren Moffat. “The Language of Science and Social Licence to Operate.” Journal of Language and Social Psychology 36, no. 1 (January 2017): 45–60. doi:10.1177/0261927X16663254.

Ronald DiPippo, 2012: Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact. 3rd ed. p. cm. ISBN 978-0-08-098206-9

RMI 2008: Communication from the Commission to the European Parliament and the Council: The raw materials initiative — meeting our critical needs for growth and jobs in Europe {SEC(2008) 2741} Link (accessed 29.04.2019):

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52008DC0699&from=EN

Renewable Heating & Cooling Platform (Alex Aposteanu, Inga Berre, Ruggero Bertani, Christoph Clauser, Florence Jaudin, Attila Kujbus, Burkhard Sanner, Javier Urchueguia ), 2014: Geothermal Technology Roadmap - European Technology Platform on Renewable Heating and Cooling. Link (accessed 29.04.2019):

http://www.rhc-platform.org/fileadmin/Publications/Geothermal_Roadmap-WEB.pdf

Massachusetts Institute of Technology, 2006: The Future of Geothermal Energy - Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. ISBN: 0-615-13438-6. Link (accessed 29.04.2019):

https://energy.mit.edu/wp-content/uploads/2006/11/MITEI-The-Future-of-Geothermal-Energy.pdf

John Ziagos, Benjamin R. Phillips, Lauren Boyd, Allan Jelacic, Greg Stillman, Eric Hass, 2013: Technology Roadmap for Strategic Development of Enhanced Geothermal Systems. Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-198. Link (accessed 29.04.2019):

https://www.energy.gov/sites/prod/files/2014/02/f7/stanford_egs_technical_roadmap2013.pdf

International Energy Agency, 2011: Technology Roadmap Geothermal Heat and Power. Link (accessed 29.04.2019):

https://www.iea.org/publications/freepublications/publication/Geothermal_Roadmap.pdf

Gerd Rosenkranz, 2015: Megatrends in the global energy transition. Published by WWF Germany and LichtBlick SE. Link (accessed 29.04.2019):

https://energiewendebeschleunigen.de/Downloads/151201_Megatrends_der_Energiewende_EN.pdf

World Economic Forum, 2015: Mining & Metals in a Sustainable World 2050. REF 250815. Link (accessed 29.04.2019):

http://www3.weforum.org/docs/WEF_MM_Sustainable_World_2050_report_2015.pdf

CSIRO Futures, 2017: Mining Equipment, Technology and Services - A Roadmap for unlocking future growth opportunities for Australia. Link (accessed 29.04.2019):

https://www.csiro.au/~/media/Do-Business/Files/Futures/METSRoadmap.pdf?la=en&hash=DDDFFA37409C84571F22DA3FED16EA66C346C816

European Commission, Directorate-General for Research and Innovation, 2011: Global Europe 2050. Socio-economic Sciences and Humanities. EUR 25252. Link (accessed 29.04.2019):

https://ec.europa.eu/research/social-sciences/pdf/policy_reviews/global-europe-2050-report_en.pdf

European Commission, 2012: Energy roadmap 2050. DOI:10.2833/10759. Link (accessed 29.04.2019):

https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf

John Finger, Doug Blankenship, 2010: Handbook of Best Practices for Geothermal Drilling. Sandia National Laboratories, SAND2010-6048. Link (accessed 29.04.2019):

https://www.energy.gov/sites/prod/files/2014/02/f7/drillinghandbook.pdf

Lilian Aketch Okwiri, 2017: Risk Assessment and Risk Modelling in Geothermal Drilling. MSc thesis, Iceland School of Energy, School of Science and Engineering, Reykjavik University. ISBN 978-9979-68-415-2 . Link (accessed 29.04.2019):

https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2017-02.pdf

IGA Service GmbH, 2013: Geothermal Exploration Best Practices: A Guide to Resource Data Collection, Analysis, and Presentation for Geothermal Projects. Link (accessed 29.04.2019):

https://hub.globalccsinstitute.com/sites/default/files/publications/138043/geothermal-exploration-best-practices-guide-resource-data-collection-analysis-presentation-geothermal-projects.pdf

P. Nami, R. Schellschmidt, M. Schindler, T. Tischner, 2008: Chemical Stimulation Operations for Reservoir Development of the Deep Crystalline HDR/EGS System at Soultz-Sous-Forés (France). Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 28-30, 2008, SGP-TR-185. Link (accessed 29.04.2019):

https://pdfs.semanticscholar.org/055f/011a306fe5056fb0eb1ca29a88d5d0269dc2.pdf

Christopher Rochelle, Andrew Kilpatrick, Jeremy Rushton, Alicja Lacinska, Dániel Fűzéri, Simon Chenery, Andrew Marriot, Elliott Hamilton, Michael Watts, Ian Mountney, Simon Kemp, 2017: Report on metal content mobilisation using mild leaching. CHPM2030 Deliverable D2.2. (accessed 29.04.2019):

https://www.chpm2030.eu/wp-content/uploads/2018/03/CHPM2030_D2.2.pdf

Einar Gunnlaugsson, Halldór Ármannsson, Sverrir Thorhallsson, and Benedikt Steingrímsson, 2014: Problems in Geothermal Operations - Scaling and Corrosion. Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014. Link (accessed 29.04.2019):

https://orkustofnun.is/gogn/unu-gtp-sc/UNU-GTP-SC-18-19.pdf

Tevfik KAYA, Pelin HOŞHAN, 2005: Corrosion and Material Selection for Geothermal Systems. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005. Link (accessed 29.04.2019):

https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/2039.pdf

Grigory V. Tomarov, Dmitry V. Kolesnikov, Valery N. Semenov, Viktor M. Podverbny, Andrey A. Shipkov, 2015: Prevention of Corrosion and Scaling in Geothermal Power Plants Equipment. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015. Link (accessed 29.04.2019):

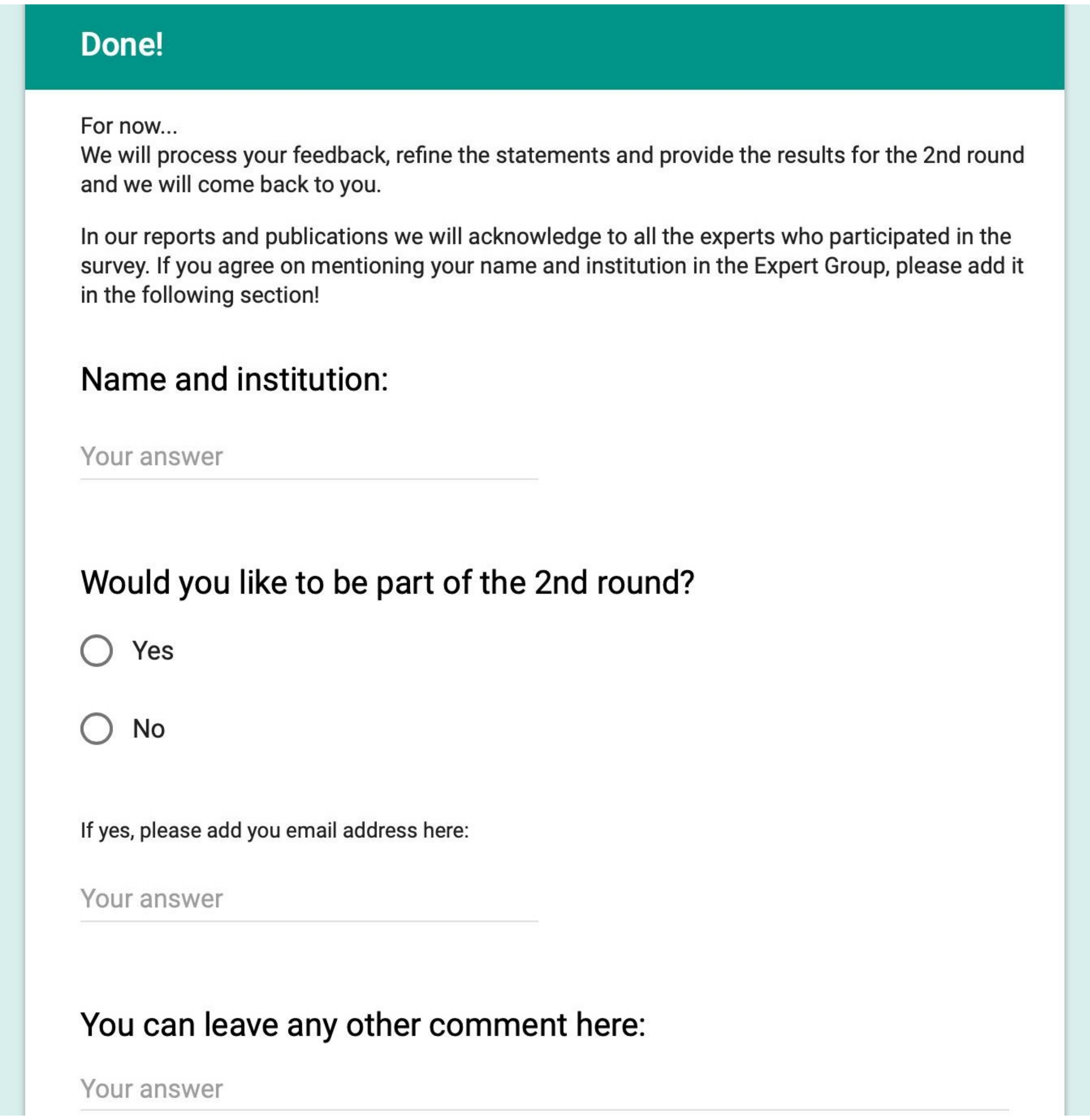
https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/27032.pdf

## List of appendix

### 1. Delphi survey Expert group: list of participants

At the end of each forms (round 1 and 2), there was an opportunity for the participants to provide their name and organization (Figure 51 and 52), so they would be acknowledged for the participation in the report.

We acknowledge to all Expert participated in the research of the future of CHPM technology. Their input is highly appreciated for the work of CHPM2030 project, WP6. They will also receive the final reports, once submitted to the EC.



Done!

For now...
We will process your feedback, refine the statements and provide the results for the 2nd round and we will come back to you.

In our reports and publications we will acknowledge to all the experts who participated in the survey. If you agree on mentioning your name and institution in the Expert Group, please add it in the following section!

Name and institution:

Your answer

Would you like to be part of the 2nd round?

- Yes
- No

If yes, please add you email address here:

Your answer

You can leave any other comment here:

Your answer

*Figure 51: Final page of CHPM2030 Delphi survey, round 1*

## Almost done! Few more things before submission...

### Propose location for CHPM technology application.

Are you aware of locations(s) where CHPM technology could be applied, with deep mineral enrichment and geothermal potential? Please propose it below with a short description, why it is interesting, and we will include it in the database for prospective CHPM locations.

Your answer

### Acknowledgment: name, institution

In our reports we will acknowledge to all the experts who participated in the survey. If you agree on mentioning your name and institution at the Expert Group, please add it in the following box!

Your answer

### Would you like to receive the results of this Delphi survey? @

If yes, write your email address below.

Your answer

## Thank you for participating in the research for the future of Combined Heat, Power and Metal extraction technology!

For any other feedback or question, please contact Tamas Miklovicz (tamas.miklovicz@lapalmacentre.eu) or Marco Konrat (marco.konrat@lapalmacentre.eu) from La Palma Research Centre (www.lapalmacentre.eu) who are coordinating this Delphi survey.

For project related question you can contact the coordinator, Éva Hartai (foldshe@uni-miskolc.hu). You can find more about the project at the website: www.chpm2030.eu

Data Protection Notice: Your personal/work data (email, name, institution) is collected on a voluntarily bases, only for the above mentioned purpose. It will be kept safe and not transferred to any third party.

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*Figure 52: Final page of CHPM2030 Delphi survey, round 2*

*Table 5. List of participants in CHPM2030 Delphi survey, round 1-2, alphabetic order.*

| Name | Organisation | Name | Organisation |
|---|---|---|---|
| **Alvin Remoroza** | Energy Development Corporation | **Janos Szanyi** | University of Szeged |
| **Antoine Bouvier** | Senior consultant | **Jaromir Tvrdy** | GET s.r.o. Prague |
| **Árni Ragnarsson** | ÍSOR, Iceland Geosurvey | **Jean Pierre Tutusaus** | MIRA international |
| **Attila Kujbus** | Geothermal Express Ltd. | **Jean-Philippe Gibaud** | GEOLITH |
| **Augusto Bento Filipe** | LNEG - Laboratório Nacional de Energia e Geologia | **Jim Randle** | Private geothermal consultant |
| **Balazs Kobor** | | **João Carvalho** | LNEG - Laboratório Nacional de Energia e Geologia |
| **Ben Laenen** | VITO | **José F. Albert-Beltrán** | Instituto Volcanológico de Canarias |
| **Benno Kathol** | Geological Survey of Sweden (SGU) | **Jose Pablo Fernandez** | Grupo Dragon |
| **Benoît Valley** | University of Neuchâtel | **Krzysztof Galos** | Mineral@Energy Economy Research Institute, Polish Academy of Sciences, Polish |

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| | | | Association of Mineral Asset Valuators |
| **Bernd Schuermann** | AMSTRA Environment & Mining | **Lakshman Ravi Teja Pedamallu** | University of Coimbra. |
| **Bogdan Lelyk** | GEO-DELTA-KB LLC | **Laurent Scheurer** | CHGEOL |
| **BOISSAVY** | | **Liz Lappin** | |
| **Cesar Andrade** | University of the Azores | **Luca Guglielmetti** | |
| **Chris Rochelle** | British Geological Survey | **Luis Carlos Gutierrez-Negrin** | GEMex Project, UMSNH, Mexico. |
| **Christoph Bott** | BDG (Berufsverband Deutscher Geowissenschaftler e.V.), Germany | **Luís Lopes** | La Palma Research Centre |
| **Daniel P. S. de Oliveira** | LNEG - Laboratório Nacional de Energia e Geologia | **Macovei Monica** | Geological Survey of Romania |
| **Dejan Milenic** | Faculty of Mining and Geology, Serbia | **mag. Andrej Lapanje** | Geological Survey of Slovenia |
| **Diana Persa** | Geological Institute of Romania | **Mara van Eck van der Sluijs** | DAGO |
| **Dogacan Ozcan** | İstanbul University | **Mariene Gutierrez** | Tlalli Energia |

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| **Dr David McNamara** | National University of Ireland Galway | **Mate Lesko** | Hungarian Geological Society |
| **Dr P. B. Sarolkar** | | **Mathieu Bellanger** | TLS-Geothermics |
| **Dr Prafulla B. Sarolkar** | Director General, Geological Survey of India | **Miro Sferle** | TRANGEX - Oradea - Romania |
| **Dr. Andres Navarro** | Polytechnical University of Catalonia | **Miroslav Raus** | CAEG |
| **Dr. Ing. Sebastian Homuth** | Züblin Ground Engineering GmbH, Frankfurt, Germany | **NIna Rman** | Geological Survey of Slovenia |
| **Dr. Jenő Csongrádi** | free-lance consultant geologist | **Paul Gordon** | SLR Consulting |
| **Dr. Kai Zosseder** | Technical University Munich | **Peter Meier** | Geo-Energie Suisse AG |
| **Dr. Sebastian Homuth** | Züblin Ground Engineering | **Peter Müller** | BDG (Berufsverband Deutscher Geowissenschaftler e.V.), Germany |
| **Dusan RAJVER** | Geological Survey of Slovenia | **Peter Scharek** | Hungary, Geological Survey of Hungary |
| **Els Ufkes** | KNGMG | **Philippe Pasquier** | Polytechnique Montréal |
| **Elsa Cristina** | LNEG - Laboratório | **Prof. dr Stanislaw** | Miedzicopper Corp. |

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| **Ramalho** | Nacional de Energia e Geologia | **Speczik** | al Jerozolimskie 96 00-807 Warsaw Poland |
| **Enrique Tello Hinojosa** | Federal Electricity Commission, Mexico | **Prof. Krzysztof Szamałek** | Polish Geological Survey |
| **Eoin McGrath** | Aurum Exploration | **Prof. Mirko Vaněček** | |
| **Eren Gunuc** | Geoexpect Consulting Services | **Racquel N. Colina** | Energy Development Corporation, Philippines |
| **Éva Hartai** | University of Miskolc | **Rafael Branco** | |
| **F. Schoof** | | **Riccardo Pasquali** | Terra GeoServ Ltd - Geothermal Association of Ireland |
| **János Földessy** | University of Miskolc | **Richard Shaw** | British Geological Survey |
| **Fausto Ristagno** | Geothermal Energy Consulting srl | **Rita Caldeira** | LNEG - Laboratório Nacional de Energia e Geologia |
| **Fidel Grandia** | Amphos21 Consulting | **Romerico C. Gonzalez** | Thermaprime Drilling Corporation |
| **Filipe Pinto** | ICT (Institute of Earth Sciences) | **Stefan Heuberger** | ETH Zürich |
| **George Catalin Simion** | Geologial Institute of Romania | **Stefan Marincea** | Geological Institute of Romania |

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| **Gerhard Schwarz** | Geological Survey of Sweden (SGU) | **T.M. Gunderson** | Epoch Energy |
| **Gorazd Žibret** | GeoZS | **Tamás Madarász** | University of Miskolc |
| **Graeme Beardsmore** | University of Melbourne | **Tamas Medgyes** | University of Szeged |
| **Graeme Scott** | GNS, New Zealand | **Terry Aimone** | Consultant to Cabo Drilling Corp |
| **Guy franceschi** | | **Thomas Bloch** | St.Galler Stadtwerke (St.Gallen, Switzerland) |
| **H.G.Dill** | University of Hannover | **Thomas Reinsch** | GFZ German Research Centre for Geosciences |
| **Halldór Ármannsson** | ÍSOR, Iceland Geosurvey | **Véronique Tournis** | Consultant |
| **Horst Rüter** | HarbourDom GmbH, Germany | **Vitor Correia** | EFG |
| **Imre Gombkötő** | | **Vojtěch Wertich** | MinPol GmbH. |
| **János Horváth** | Senior consultant geologist, Geo-Montan Ltd, Hungary | | |
| Other organisations | | | |
| Akita University | GEOLITH - Innovative processes for lithium | International Geothermal Centre | Serbian Geological Association of EFG |

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| | production | (GZB) | |
| EGEC | Geological Survey of Spain | KU Leuven | Sveriges geologiska undersökning SGU (Geological Survey of Sweden) |
| FLN Consultants | GFZ Potsdam | Ministry of Mining and Energy, Serbia | |

## 2. List of proposed locations for CHPM technology in The Delphi survey, round 2

At the end of the Delphi surveys, participants were also asked to suggest locations(s) where CHPM technology could be applied, given that there is a deep mineral enrichment and geothermal potential. This is a very valuable input for the project and we acknowledge all participants who suggested such area!

List of proposed locations for CHPM application and corresponding participants:

1. *Any locality in the Czech Republic (Miroslav Raus).*
2. *Beius area - Romania. At Beius there are drilled three geothermal wells. Could be extended the geothermal research for EGS at the basement of the geothermal reservoir, combined with deep mineral extraction (Miro Sferle -Geologist - TRANGEX - Oradea - Romania).*
3. *Beius, Bihor County, Romania (Diana Persa, Geological Institute of Romania).*
4. *Cornwall, UK. A relatively well described mineral province, with ongoing geothermal exploration in granites. Local population long involved with exploitation of the subsurface. Geothermal water and the development of spas would integrate well with the local tourist industry (Chris Rochelle, British Geological Survey).*
5. *Deep Cu-Ag mineralisation sites in central Poland (south of Pozna town) (Krzysztof Galos, Mineral@Energy Economy Research Institute, Polish Academy of Sciences).*
6. *Extreme high potential geothermal áreas, e.g. Island.*

7. *Evaluate using existing deep geothermal installations for first demonstrations of the technologies needed to extract metals from brines (e.g., Soultz-sous-forêts, Balmatt, ...) (Ben Laenen, VITO)*
8. *I don't have any particular locations in mind, but I would suggest that you have a very good look at Greece (milos island) and Turkey.*
9. *I have not the specific location. (Serbian Geology Association of EFG).*
10. *I'm not sure how deep the well must be for CHPM. But we have a lot of geothermal wells in our company (Racquel N. Colina, Energy Development Corporation).*
11. *I'm sure there are locations where CHPM tech can be applied in Europe (Graeme Scott, New Zealand).*
12. *Iceland, Mexico (International Geothermal Centre, GZB).*
13. *In Germany mainly the North German Basin and possible the Upper Rhine Graben, the later with much lower concentrations. (Horst Rüter, HarbourDom GmbH, Germany).*
14. *In Hungary, the Recsk ore complex is a potential target. It is a combined prophyry-skarn-polimetallic system at a depth of about 1 km with high geothermal gradient (50°C/km). The porphyry mineralisation has probably a deeper continuation (Éva Hartai, University of Miskolc).*
15. *In Iceland (Peter Scharek, Hungary, Geological Survey of Hungary).*
16. *Lithium is available at a concentration of about 150 ppm in the Rhine Graben area, a single project with a flow of 6 000 m3/d represents 300 t Li/year (# 1500 t LCE/year or a value of 30 million €/y to be compared with 5 million €/year for electricity with subsidies), (GEOLITH - Innovative processes for lithium production).*
17. *Locations must be determined in a careful selection process, based on a broad database.*
18. *My best guess is near an active volcano. The magma will ensure deep supply of M while the P and H are in operations (Romerico C. Gonzalez; Thermaprime Drilling Corporation).*
19. *My idea is to locate the CHPM project in the land-site located very close to the sea. This location will allow to use the sea as a reservoir for salty water (after processing). Injection into mass rock chilled thermal water creates a lot of problems in proper work of geothermal installation. This leads to breaks in work of geothermal installation and*

*even stopping of using this installation caused by economic reasons (Prof. Krzysztof Szamałek, Polish Geological Survey).*

20. *It would be interesting to check Copernicus data (Imre Gombkötő).*
21. *Portugal, Iberian Pyrite Belt (Elsa Cristina Ramalho, LNEG Portugal).*
22. *Portugal, massive sulphide deposits. It has high concentrations of valuable metals in the geothermal rocks provided. However, the question of rock composition taken say 5km deep has to be confirmed, before such an effort can be undertaken (KU Leuven).*
23. *Possibly Eastern Belgium (Guy Franceschi).*
24. *Reykjanes, Iceland. Interesting deposition formation has been observed, and it is furthermore a site for IDDP (Iceland Deep DRilling Project) where a well in excess of 4000 m depth has been drilled although not tested yet (Halldór Ármannsson. ÍSOR, Iceland Geosurvey).*
25. *The Olympic Domain in South Australia, which hosts the world class Olympic Dam iron-oxide copper, gold, uranium deposit and is also a target for EGS developments (Graeme Beardsmore, University of Melbourne).*
26. *The technology should be tested in the Portuguese ZEE border, or even around Azores Island, where a hydrothermal source was recently found (Filipe Pinto, ICT, Institute of Earth Sciences).*
27. *UK, Turkey, Africa and a specially NZ could be a hot-spot for CHPM (Eren Gunuc, Geoexpect Consulting Services).*
28. *Upper Rhine valley: Heat from the graben structure and metals from the crystalline rocks of the Black Forest and the Vosges (Sveriges geologiska undersökning SGU, Geological Survey of Sweden).*
29. *We could propose you to focus on the Sioule project, but we need to discuss about it with the partners of TLS on that project (Mathieu Bellanger, TLS-Geothermics).*