CHPM2030 DELIVERABLE D6.2

Report on Pilots (compiled from 5 reports)

Summary:

This report presents an evaluation framework that facilitates the investigation of study areas for CHPM technology. The same methodology was applied to five areas (South West England, Portuguese Iberian Pyrite Belt, Romania Beius basin and Bihor mountains, Nautanen and Kristineberg in Sweden) evaluating their CHPM potential and characteristics. A European outlook for CHPM prospective locations has also been prepared, covering 24 countries.

Authors:

Tamas Miklovicz, *Engineering Geologists*, La Palma Research Centre, Spain.

Paul A J Lusty, *Principal Economic Geologist*, Richard B Haslam, *Structural Geologist*, Richard A Shaw, *Economic Geologist*, Eimear A Deady, *Minerals Geoscientist*, Paul Williamson, *Senior Geophysicist*, British Geological Survey.

Elsa Cristina Ramalho, *Geological Engineer*, João Xavier Matos, *Economic Geologist,* João Gameira Carvalho, *Geophysicist*, Portuguese National Laboratory of Energy and Geology.

Diana Perșa, *Researcher*, Ștefan Marincea, *Senior Researcher*, Delia Dumitraș, *Senior Researcher,* Cătălin Simion, *Researcher*, Geological Institute of Romania

Gerhard Schwarz, *Geophysicist*, Benno Kathol, *Geologist,* Magnus Ripa, *Geologist*, Bo Thunholm, *Hydrogeologist* Edward P Lynch, *Geologist,* Johan Jönberger, *Geophysicist*, Geological Survey of Sweden.

Domenico Marchese, *Project Officer*, Anita Demény, *Project Officer*, Isabel Fernandez, *Executive Director*, European Federation of Geologist

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

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CHPM: Combined Heat Power and Metal extraction technology
CHPM2030: The EU Horizon 2020 funded project under Grant Agreement nº 654100
EFG: European Federation of Geologists
LTP: Linked Third Parties
TRL: Technology Readiness Level
EC: European Commission
HS: Horizon Scanning
BGS: British Geological Survey
SGU: Geological Survey of Sweden
LNEG: Portuguese Geological Survey
IGR: Geological Institute of Romania
LPRC: La Palma Research Centre
RBINS: Royal Belgian Institute of Natural Sciences
EGS: Enhanced or Engineered Geothermal System
HDR: Hot Dry Rock
WP: Work Package

0. Preface

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

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

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

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

1. Executive summary

There are many innovative geothermal or mineral related 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 concepts that have been developed within the framework of this project aim to increase the economics of deep geothermal, especially Enhanced Geothermal Systems, projects by extracting valuable metals from the geothermal brine. The first pilot applications are envisioned by 2030 and the full-scale applications by 2050.

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, compiled from 6 documents, presents 1) an evaluation framework that facilitates the investigation of study areas for CHPM technology; 2) the description of areas from 4 countries, concerning their CHPM potential and characteristics: Cornwall in South West England, Portuguese Iberian Pyrite Belt, Beius basin and Bihor mountains in Romania, Nautanen and Kristineberg in Sweden; 3) an European outlook for CHPM prospective locations, covering 24 countries.

The baseline for this study was presented in WP1, Task 1.2 Knowledge Gaps and Updating Information: CHPM2030 Deliverable 1.2 Report on Data Availability (Schwarz et al. 2016). Here the focus was on data availability, whereas in Task 6.2 the focus was on the detailed evaluation of data. In Task 6.2 the first activity was the development of a harmonised study area evaluation template. This was an iterative process with the involvement of the technology developers and the study area representatives at consortium meetings, workshops and fieldtrips.

The final evaluation template outlines a group of important topics that must be taken into account when evaluating the CHPM potential at a given area. The topics are the following: geology and geophysics of the prospective area, deep metal enrichment, EGS potential integrated 3D-4D model, information for CHPM technological elements (underground heat exchanger (deep metal enrichment + potential reservoir), production and injection wells, Electrolytic metal recovery and gas diffusion electro-precipitation, power plant, salt gradient power generation), operational characteristics (environmental, social and political background, financial aspects), with numerous subtopics and a short description.

The report on south-west England, considered the availability of geoscience information, the geological environment, geothermal characteristics, potential for deep metal enrichment, and technical, environmental, social and regulatory factors that could influence the future development of CHPM extraction technology in the region. South-west England was selected as the UK CHPM2030 study area as it is a major magmatic province, with high heat production, and hosts extensive polymetallic mineralisation. The study area is extensively mineralised, hosting the highly productive Camborne-Redruth mining district. The Carnmenellis granite was the focus of a major geothermal experiment, the UK hot dry rock (HDR) research and development programme that ran for more than 15 years, and produced a huge amount of data and analysis on the geothermal energy potential of south-west England. A contemporary project, operated by Geothermal Engineering Ltd, is the United Downs Deep Geothermal Power (UDDGP) project, located near Redruth. The temperature of the Carnmenellis granite at 5 km depth is estimated to be 200^{o}C. Cornish granites typically have very low primary permeability, but relatively high hydraulic conductivity as a result of faults and joints. Fluid circulation is evident in the local mines where thermal, saline brines discharge from cross-course structures. It is concluded that a dynamic system driven by convective and hydrodynamic forces has allowed continuous water-rock reaction to occur within the upper 3–4 km of the currently exposed Carnmenellis granite. These brines contain reported lithium concentrations of up to 125 mg/l^{-1}, probably as a result of the breakdown of mica during fluid-rock interaction. Preliminary modelling of the Cornubian Batholith has been undertaken to improve understanding of its properties relevant to geothermal energy development. A regional model was constructed to understand the spatial relationship of key geological parameters that were used for the development of subsequent site-scale models. One of the site-scale models is based on data from the HDR project site, and has a depth range of -1000 to -3000 mbsl. The model is centred on the HDR project boreholes, incorporating fracture data from two of the deep boreholes and site-specific hydrological properties. Data and assumptions about the fracture network were used to generate three discreet fracture network (DFN) models for the HDR project reservoir. These were up-scaled to include porosity and permeability in order to understand the potential flow pathways within the reservoir. The second site-scale model considers an area located to the NW of the Carnmenellis granite, where the current UDDGP project is located. The target geothermal reservoir is still considered to be the Carnmenellis granite, and the model covers a volume of 12 km^3, with a depth range of -1500 to -5500 mbsl. In summary south-west England, and specifically Cornwall, is an excellent location for a pilot-scale CHPM system. It has the essential prerequisites of a proven geothermal energy resource and abundant polymetallic mineralisation. It is one of the best surveyed and most data-rich parts of the UK, with a long history of mineral development and geothermal research. The local government and communities appear supportive of deep geothermal resource development, and it has a major, active co-funded deep geothermal project.

The report from Portugal provides an update of the geoscientific data and information on the South-West Iberian Pyrite Belt (IPB), a Variscan metallogenic province with massive sulphides deposits. This active mining region, with vast amount of geological information available, has a good prospect of mineralization at deeper levels, therefore of interest for CHPM technology. The chosen study area is Never-Corvo Mine due to the available 3D geological, geophysical models and its relation with EGS potential. The deposit consists of 7 massive sulphide ore lenses with copper, zinc, and lead mineralizations. The report presents the relevant geological, geophysical, mineralogical characteristics of the area to investigate the feasibility of the implementation of CHPM technology at Never-Corvo. The main interest is the existence of the deep mineralization, near the operating mine. The coproduction of energy and minerals would extend the lifetime of the mine operation. The study also presents emerging factors, such as the energy transition, financial requirements and possibilities, advancement in 3D modelling of the deposit, challenges to generate data about the deeper levels (>1.2 km), environmental, social and political background, and the possible future agreements between the mining management and the Portuguese government. There was also a synergy with the ongoing mining operations, parallel EU funded projects (SmartExploration, Explora), and the CHPM study are evaluation.

At the Romanian study areas, the Beius basin and the Bihor Mountains were investigated by IGR due to the favourable geothermal and mineral potential of the areas for CHPM technology. In the Beius Basin, the geothermal potential is high due to the thin crust, as a result of a regional extension in the Pannonian Basin, resulting high heat flow (above 80mW/m2) and elevated geothermal gradient (5.6-6.2 °C/100 m). Deep mineralization is also expected due to intrusive magmatic bodies within the Beius Basin. On the other hand, the Bihor mountains are also of interest due to the mineral deposits, which is part of the Banatitic Magmatic and Metallogenetic Belt metallogenic province. The granodiorite – granite plutonic body, formed skarn mineralisation at the contact with Mid- and Upper Triassic limestones. The identified deposit types of interest are 1) iron, boron, bismuth, molybdenum bearing skarns, and related vein occurrences with copper, zinc, lead sulphides, 2) Brucite deposits from Budureasa and Pietroasa, 3) Borate deposit from the contact of aureole of the Pietroasa granitoid body through metasomatic processes, 4) tungsten bearing and base metal skarns at Baita Bihor. Furthermore, there is an ongoing district heating system in Beius town, whose operator showed interest for the CHPM technology in the future. This shows public support for geothermal applications, indicated geological potential for heat and metals, and industry interest for the additional metal extraction technology.

In Sweden, two CHPM test sites are proposed for further investigations: These are the Kristineberg area in the Skellefte district and the Nautanen area in the Northern Norrbotten ore province. The Kristineberg area is known for its volcanogenic massive sulphide deposits (VMS). Zinc is the main target, though in some areas copper and gold ores are mined. The area was studied by geophysical methods down to 12 km and by drilling down to about 1400 m below surface. High resolution reflection seismic data outlined the VMS ore bodies and associated structures. However, the completed seismic surveys also have shown that considerable efforts were needed to acquire high quality data, preferably by 3D surveys. The operations in the Kristineberg mine have reached a depth of 1200 m, 31 million tons of ore were mined, reserves are 5 million tons and resources about 13 million tons. The combined grades of mined ore, reserves and resources are 3.9 % zinc, 0.7 ppm gold, 44 ppm silver, 0.9 % copper and 0.4 % lead. Mineralisation in the Nautanen area are part of several hydrothermal copper-gold occurrences related to the ironoxide-copper-gold (IOCG) mineral deposits. The “Nautanen North” deposit has an indicated resource of 9.6 million tons of ore grading at 1.7 % copper, 0.8 ppm gold, 5.5 ppm silver and 76 ppm molybdenum, with additional inferred resources of 6.4 million tons grading at 1 % copper, 0.4 ppm gold, 4.6 ppm silver and 41 ppm molybdenum. In both mining areas, the installation of a CHPM system is highly challenging. The low geothermal gradient of only about 16 °C/km and heat flow density of about 50 mW/m^2, typical to the Fennoscandian Shield, demand large borehole depths of at least 5 to 7 km. At such depths, there is very limited information available about geological structures, deep-seated fluids, and hydraulic conductivity of the crystalline bedrock. However, with the help of integrated geophysical studies, i.e., deep seismic and magnetotelluric measurements and in cooperation with the mining industry, many advancements were made facilitating the CHPM potential in future projects.

The European outlook for prospective CHPM potential has been prepared with the help of the EFG's Linked Third Parties, the national geological associations. In total there were 24 countries covered: Belgium, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Serbia, Slovenia, Spain, Switzerland, Ukraine, Austria, Croatia, Cyprus, Luxembourg, Slovakia, Sweden the United Kingdom. In each country, there were 3 tasks: 1) Area selection: define an area most likely to be a future CHPM candidate; 2) Basic area evaluation: the task continued with the evaluation of the basic characteristics of the selected areas; 3) CHPM characteristics: this task considered a deeper investigation and data evaluation of the most likely CHPM sites. This was a rough screening for areas that may be further CHPM site. Areas selected as "type B", has the potential for "CHM" technology and use the delivered metal extraction technological couples with direct heating application. Areas selected as "type A" may be actual areas for a full "CHPM" application, after a thorough geological, geophysical exploration that can show the ultra-deep mineral enrichment. This work has shown a number of areas that has potential to develop a CHPM site, but the lack of publicly available data may still represent a bottleneck to improve the knowledge needed implement CHPM technology at any of the selected sites. The identified areas have been gathered in a publicly available online database: http://bit.ly/CHPMinfoplatform.

It has been found that a new type of exploration mindset is required for undertaking such survey. Exploration at areas for combined heat, power and metal extraction will have to use the traditional surveying and interpretation methods, but it must improve on them, and combine tools from both geothermal and mineral exploration campaigns, to create a comprehensive strategy. The first step for that was the creation of the evaluation template, which served as a “checklist” for important characteristics to consider when looking into CHPM potential. The 5 study areas from 4 countries have been evaluated according to this new strategy and each area has the potential to develop actual CHPM pilots in the future. Each area has its unique characteristics, and all have substantial amount of information available publicly from the top 1 km of the crust, providing a good understanding of the near surface. The next challenge thus is to extend this understanding at deeper levels, run new, preferably 3D surveys, further advance each predictive 3D models for a downwards continuation. With the help of these study reports and the European outlook study, the following items have now been clarified: 1) the information available at each area, 2) the CHPM potential based on this geoscientific data, 3) remaining gaps to be overcome in the future. Based on this knowledge, the idea of pilot implementation can be further advanced through concrete recommendations in the CHPM2030 roadmaps (CHPM2030 Deliverable 6.3). The next exploration/research projects can continue, based on these recommendations and the CHPM pilot readiness level can be achieved by 2030.

2. Introduction

Work Package 6 Roadmapping and Preparation for Pilots aims to set the ground for CHPM pilot implementation following the EC-funded period. Such follow-up planning is necessary, because 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. This is done through the creation of a technology roadmap that outlines desired future visions and targets and the actions that will need to be made in order to arrive to this vision (pilot and commercial readiness level by 2030 and 2050 respectively). This is the main result of the work package. In order to deliver this roadmap document, several complementary steps needed to be undertaken along Task 6.1 and Task 6.2 (Figure 1).

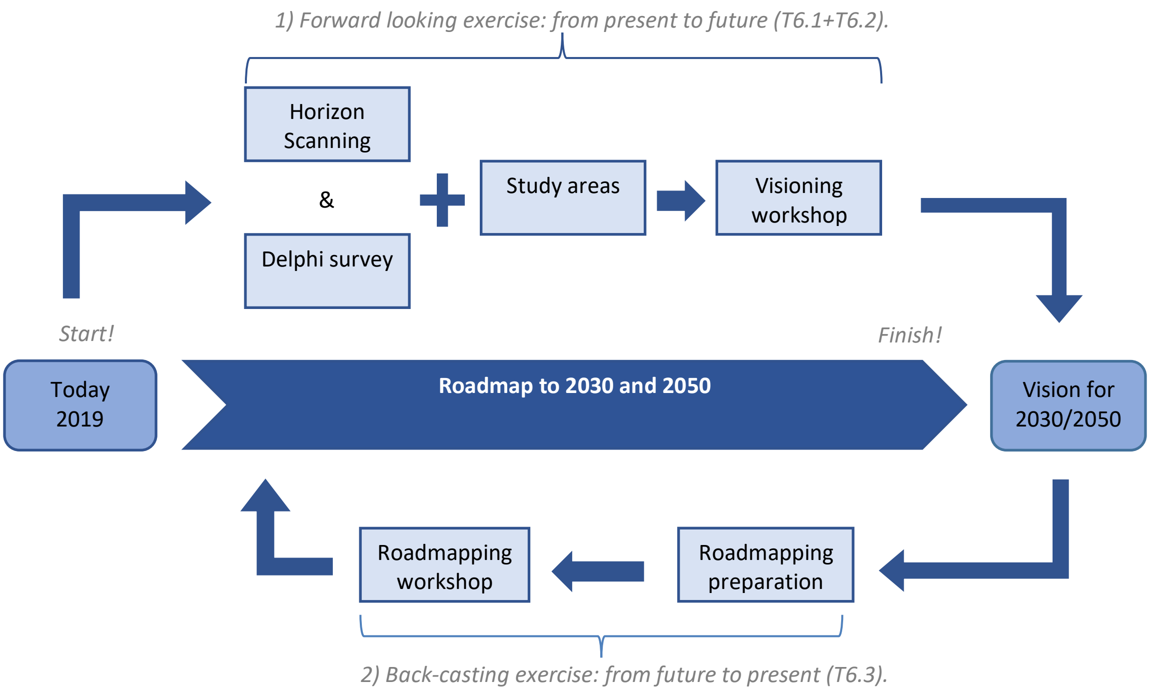

Figure 1: WP6 Roadmapping and Preparation for Pilots workflow

The first forward looking exercise started from the present technological baseline towards the future, with the help of Horizon Scanning, Delphi survey, Visioning. Horizon Scanning provided the present technological baseline, with an expert workshop on mapping key interest areas and gap analysis. The results have been formulated into Delphi statements covering various aspects of the technology. The 2-round Delphi provided more pieces of the puzzle of what the future may be at key interest areas. The next step was the organisation of a Visioning workshop where the Experts defined preferred targets for two timeframes to enable the technology implementation at TRL6-7 by 2030, and TRL8-9 by 2050. The sum of the targets is the Vision that describes the desired targets in the future. This line of activities includes Task 6.2, investigating potential pilot areas (Cornwall in South West England, Portuguese Iberian Pyrite Belt, Beius basin and Bihor mountains in Romania, Nautanen and Kristineberg in Sweden), with a European outlook for the application of CHPM technology in the future, with the development of a harmonised study area evaluation template document.

The second line of activities started at the desired vision in the future, and used a roadmapping workshop and back-casting exercise to identify, what actions need to be taken in order to arrive to the desired future destination (Vision), with the pre-assessed study areas and other prospective locations across Europe (as identified by EFG LTPs), through emerging issues (Delphi) from the technology baseline of today (HS). The roadmap document is building on Deliverables 6.1 and 6.2.

In WP6, the two main lines of activities were the preparation and implementation the Horizon Scanning, the 2-round CHPM2030 Delphi survey, Visioning workshop; and the formulation of a 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 and the review and integration of *WP1 Methodology framework definition* baseline.

3. Methodology and objectives

3.1. Summary of WP1 findings

In WP1, under Task 1.2 Knowledge gaps, updating information the focus was on data availability and screening for potential areas. In Deliverable 1.2 Report on Data Availability (Schwarz et al. 2016), a brief overview was provided about the four major ore districts in Europe: SW England, Southern Portugal, NW Romania and Central and Northern Sweden.

The report aimed at setting the ground for identifying future CHPM sites through investigating the following points: previous research and unprocessed data (drilling, geophysics); structural settings, geometry, composition of ore deposits; current 3D metallogenic (predictive) models; extending existing models to greater depth; understanding knowledge gaps and limitations; mineralisation, deep seated faults, fracture zones; past and present tectonics, deep fluid flow, heat flow, temperature. Nevertheless, some major questions left to be answered, mostly related to the uncertainties coming from the CHPM relevant depths, spatial distribution of structures and lithologies, details of mineralisation, physical properties and their characterization (temperature, electrical conductivity, seismic velocity).

The four country reports (*Appendices D1.2.1 to D1.2.4*) describes that the general geology of each selected study area, future potential pilots, are well known and documented. These selected areas are located in three large metallogenic provinces in Europe:

- Precambrian Fennoscandian Shield province, as for the Swedish study area;
- Late Paleozoic Variscan province, as for Cornwall and southern Portuguese study areas;
- Mesozoic-Cenozoic Alpine province, as for NW Romanian study area.

These selected areas have been investigated according to the CHPM technology objectives, focusing on the geothermal potential geological data and description of the mineralized areas. The second also includes description of ongoing geophysical efforts for increasing resolution at CHPM relevant depths (3-6 km) at the mineralised zones.

Beside the four study areas, the Linked Third Parties (LTPs) of the European Federation of Geologists (EFG) attempted to create an inventory of drill holes where temperatures exceeded 100°C and/or metal enrichment was encountered at depth. This investigation was performed at 24 European Countries. The National Associations collected publicly available geological data at national level on deep drilling programs, geophysical and geochemical explorations and other relevant geo-scientific data on geothermal potential and deep mineral enrichment (Appendix D1.2.5 Report on Data Collection by the EFG Linked Third Parties).

As a general observation, geological data at deeper levels (>1km) is very limited. However, at shallower levels, the geology, mineralisation, fluids, geothermal potential is well documented at the investigated sites, which is freely and openly available. It was identified that the structural information and the knowledge of the physical state of the upper crust have significant improvement in order meet CHPM requirements.

In WP6, under *Task 6.2 Preparation for pilots* the focus shifts towards Data Evaluation for CHPM potential of the study areas and Europe wide. Since there was already a good description on the geology, mineralization, geothermal potential and CHPM relevant data availability of the study areas and LTPs (D1.2 Report on Data Availability), the core question in Task 6.2 was the following: how to advance the study area evaluation from the solid baseline which has been provided in WP1.

In addition to the previous point, there has been new advancements in the CHPM technology by the Consortium, with better understanding on the data requirements of the technological components (metal mobilisation and extraction, baseline economics, environmental considerations and system integration). Parallel to the technological development, there has been also new insight from the foresight process from Task 6.1.

Since many of the study areas are at active mining and/or geothermal development areas, since the submission of D1.2, new results and geological data become available, that has been used in this study.

Therefore, in Task 6.2 the first objective here was to gather ideas, strategies on the core question of T6.2: how to advance the study area evaluation from the solid baseline which has been provided in WP1.

3.2 Developing the evaluation template

This subtask represents the short-term planning to "set the ground for subsequent pilot implementation" and builds on the result of D1.2 Report on Data Availability (including South West England, Portugal, Iberian Pyrite Belt, Romania, Sweden, Report on data availability of drill holes: Europe integrated Annexes) and D2.4 Report on Overall System Dynamics. In Task 6.2 Preparation for Pilots the focus is on Data Evaluation for CHPM potential of the Study Areas and Europe wide. The objective of Task 6.2 is to support the development of technology and economic feasibility for pilot implementation of such system, in order to generate discussion on financing such project. This objective is engaged through the following actions:

- Developing a framework that harmonise and guide the area evaluation for CHPM prospect,
- In-depth evaluation of of four areas according to the evaluation framework,
- Selection and basic evaluation of European potential areas by the EFG LTPs

- Creation of a spatial database on European scale of prospective CHPM areas, including information from the study areas and LTPs.

The first task, parallel to continue working at the study areas by British Geological Survey, Portuguese National Laboratory of Energy and Geology, Geological Institute of Romania, Geological Survey of Sweden, was the development of a common framework, a template for evaluating a study area for CHPM potential. Due to the novelty of the task, a common framework or template is required in order to 1) evaluate the areas according to the CHPM2030 consortium common knowledge, 2) harmonized work: structured reports and better area comparison and compatibility. This document outlines the topics that are important to cover when evaluating an area for CHPM potential.

After internal preparation at LPRC, the work started with email communication and online meetings between LPRC, UNIM and the four study area representatives during December, January and February 2018. It was important to discuss this with the partners in this subtask and build a common strategy, since such kind of evaluation/exploration work has not been done before.

Work meetings and field trips

By the time of the Lanzarote Consortium meeting (22-23 March 2018), a draft template was prepared by LPRC, based on partners input. On the second day at the T6.2 workshop, all partners participated in the refining of this template. In WP1 the main objective was to survey data availability on these areas, whereas in WP6 the effort shifts to data evaluation. In order to create a consistent assessment of each site, an evaluation framework has to be set up, which was the aim of this workshop. The idea was to generate meaningful discussion between the technology developers (VITO, KU Leuven, UNIM, USZ, ÍSOR, MinPol) and the study area representatives (IGR, SGU, LNEG, BGS, EFG), in a matchmaking exercise. The former represented a set of requirements on what they want to know about an area, before deploying CHPM technology, the latter represented data availability from a concrete site. The discussion was following the themes of the template, and it reflected at each point on the study areas. The work has been split into two groups and facilitated by the moderators from LPRC.

Figure 2: Lanzarote Consortium meeting and workshop participants (22-23 March 2018)

The results of the Lanzarote T6.2 workshop has been used to update the template with the input from both technology representatives and study area representatives. The updated template was again presented at the EFG orientation workshop for the Linked Third Parties in Brussels (12 April 2018). The objective for the LTPs is to develop a study and a spatial database on European scale of prospective CHPM areas. EFG LTPs assess the geological data on suitable ore-bearing formations and geothermal projects- collected in WP1, in relation with the potential application of the CHPM technology.

The aim of the one-day workshop was to update the LTPs about the recent development of the project and to create guidelines and instructions for CHPM prospective areas selection & evaluation. The LTPs were introduced to the scope of their involvement through presentations from UNIM (Éva Hartai: general project presentation, Tamas Madarász: Technological elements and system dynamics), SGU (Gerhard Schwarz: Data Availability, Summary of the Country Reports), LPRC (Tamas Miklovicz: Aim and Structure of WP6) and EFG (Anita Demény: CHPM Site Selection, Investigation Framework and Data Assessment). After the presentations, interactive group work followed.

Figure 3: Brussels workshop participants (12 April 2018)

The workshop was divided in two parts: area selection and area evaluation for CHPM technology application. The first part was an example-led discussion, while the LTPs were given incomplete information about different geological cases and they were asked to decide whether it was of interest for the project or not. During the second exercise, the discussion was about the evaluation template, and the LTPs were asked to gather ideas/comments and gaps/limitations related to the topics. The workshop was facilitated by EFG and LPRC.

Table 1: Countries included in the European outlook for prospective locations

EFG LTPs involved in CHPM2030 (16+1)			Data collected by RBINS (7)
• Belgium • Czech Republic • Finland • France (by EFG) • Germany • Greece	• Hungary • Ireland • Italy • The Netherlands • Poland • Portugal	• Serbia • Slovenia • Spain • Switzerland • Ukraine	• Austria • Croatia • Cyprus • Luxembourg • Slovakia • Sweden • United Kingdom

After the workshop the template was finalised and the three LTP tasks were outlined:

1. area selection of prospective CHPM areas

EFG Linked Third Parties were asked to define at minimum 1, but maximum 6 prospective CHPM areas in their country, and have to indicate the requested information on these areas in the Prospective CHPM areas table. If more than 6 areas were identified in the country, all of them can be indicated into the prospective CHPM areas table, but the area assessment, which was the upcoming task, had been done only for the 6 most suitable areas. The main parameters have to be taken into consideration during the prospective CHPM area(s) selection are 1) the existence of deep metal enrichment(s): degree of the mineralization, and type of mineralization; 2) the temperature: considering the possibility of heat and power production (type A: T > 100 °C) or only heat production (type B: 100 °C > T > 50 °C).

However, it is important to mention that this area selection for prospective areas, was a rough screening for areas that may be further investigated in the future. Areas selected as “type B”, has the potential for use “CHM” technology and use the delivered metal extraction technological couples with direct heating application. Areas selected as “type A” may be actual areas for a full “CHPM” application, after a thorough geophysical exploration that can show the ultra-deep mineral enrichment. On the other hand, if the requirements were set too high (T > 170 °C + indicated metal enrichment), many potential areas would have been ruled out due to the lack of information or direct evidence at such depths.

2. evaluation of basic characteristics of prospective CHPM areas

The second task was to describe prospective CHPM areas in their country. EFG Linked Third Parties reported on the 6 most suitable areas (from the previously identified list), and completed the evaluation of the basic characteristics of the areas. During the evaluation, LTPs to followed the template (Template for evaluation of basic characteristics of prospective CHPM areas), provided by EFG.

3. evaluation of CHPM characteristics of prospective CHPM areas

All EFG Linked Third Parties defined prospective CHPM areas in their country and filled out the Prospective CHPM areas table in the Guidelines for the selection of prospective CHPM areas. During task 2 and 3, EFG LTPs provided input according to Figure 4.

Evaluation of basic characteristics	Evaluation of CHPM characteristics
CHPM geology → local geology (in regional context) → target formation → available cross sections, geological maps, geochemical results, lithological information **CHPM geophysics** → previous geophysical measurement (in CHPM relevance) → what measurements can be used and how to locate/define the ultradeep orebody/heat exchanger → available geophysical maps, cross sections, logs, etc. **Deep metal enrichment** → (expected) metal enrichment based on available geophysical, geological, drill data, samples information, geochemistry **Integrated 3D-4D model** → existing 3D models of the target area and of the deep metal enrichment **EGS geothermal potential** → EGS potential (heat & energy) of the area → geothermal characteristics (temperature gradient, heat flux, stress field, water availability, EGS geology) → presence of deep fluids/brines, fracture system, crustal permeability	**Operational characteristics: expected design parameters** → **Expected design parameters of the CHPM technological building blocks** • underground heat exchanger • production + injection wells • electrolytic metal recovery • gas diffusion electro-precipitation • power plant (heat exchanger) • local heat and electricity demand • salt gradient power generation → **Environmental, social and political background** • gaseous and solids emissions • water and noise pollution • land and water use • induced seismicity/landslides, subsidence • public acceptance • political support • legislation, regulatory framework → **Financial aspects** • local demand for heat and electricity

Figure 4: EFG LTP evaluation template chapters.

Parallel to the EFG LTP area selection and evaluation, the partners were working on the in-depth evaluation of the 4 selected study areas. The CHPM2030 partners met in Cornwall between the 22-24th of May, to study the Cornubian granite province, which is a potential CHPM site in the future. The field trip was led and hosted by Eimear Deady and Richard Shaw from the British Geological Survey. The field trip was a good opportunity to further develop the evaluation template through informal discussion after the field activity.

The first day started at the United Downs geothermal project site. This site is being prepared for a geothermal drilling operation. The well doublet goes into the Carnmenellis granite body and the produced hot water will fuel a demonstration power plant with 1 megawatt of electric power. The next stop from the field trip was at the Carn Brea viewpoint where the tectonic setting, geology and mineralization in the area around the Camborne-Redruth mining district was explained. Next, the partners visited the famous Crowns engine houses at Botallack and had a guided tour at the Geevor tin mine, including ore processing facilities and underground tunnels. In the evening, the CHPM2030 partners had the opportunity to network with industry representatives in Cornwall, including the Cornish Lithium, GeoScience Limited, Avalon Science Limited, Camborne School of Mines and EGS Energy.

On the second day, the group visited the old HDR site at Rosemanowes Quarry in the Carnmenellis Granite. The deep drill holes, (>2000 meters), are still open and perfect for Avalon Science Limited to test and calibrate their latest cutting edge equipments. The next stop was at the Wheal Jane mine water treatment plant. Wheal Jane was a tin mine, which closed in 1991. The water is currently being pumped from the mine and treated in surface facilities. During the afternoon the partners studied the porphyritic biotite granite at Cligga head. Sheeted greisen tin-tungsten (Sn-W) and tin-tungsten-copper (Sn-W-Cu) can be observed with sulphide mineralization.

Figure 5: Participants of the Cornwall field trip (22-24th of May 2018)

The second day finished with a discussion about the study area's evaluation strategies related to WP6 – Roadmapping and Preparation to Pilots. It was concluded that it is important to integrate all available "geo" data into an existing/new 3D/4D model for better understanding the picture as a whole, to help the deeper extrapolation, for better conceptual understanding, test the theories from the area, visualize data, create new and tangible results of the area. Many other aspects have been discussed, including the importance of deep water availability, surface fresh water for the GDEx technology, social and political acceptance and support locally, access to grid, local heat/electricity demand, potential environmental risks, targeting for micas as geological sink for many elements, and more. The field trip was closed with the visit to Rinsey Cove, where it could be observed how the Tregonning-Godolphin Granite intruded into the local metasedimentary rocks, and their interaction.

The CHPM2030 project participants visited the second study area for WP6 in Beius Basin, Romania (25-26 July 2018). The field trip was organised by Diana Persa and Stefan Marincea from the Geological Institute of Romania, with the focus was on the Romanian banatitic magmatic and metallogenic belt.

The participants first visited the town hall of Beius, located on the Northwest of Romania, where the local geothermal district heating system and its instrumentations was explained. The field program included visits to several skarn related exposures of the banatitic magmatism, including Budureasa (Valea Mare, quarry with brucite bearing granodiorite-dolomite contact), Pietroasa (Dealul Gruiului, adit for exploiting magnesian borate bearing altered dolomite) and Baita (marble quarry, calcic skarns with base metal sulphides) in the Bihor Mts. and at Cazanesti (Cerboaia Valley, gehlenite bearing high temperature contact zone) in the Magureaua Vatei area. These skarns are especially interesting, as these are expected to be present 3-5 km depth at the host rock and magmatic intrusion contact zones. Since many of the surface exposure skarns were mineralised, it is expected to see similar processes at depth, being a special interest area for simultaneous geothermal energy and mineral extraction, the aim of the CHPM technology. In the end of the field day, the Romanian team presented the current stage of their 3D modelling efforts. Besides the field exposures, the participants had the opportunity to visit the Turda salt mine, the Bears' Cave at Chiscau and the Gold Museum in Brad.

Figure 5: Participants of the Romania field trip (25-26 July 2018)

Beside personal meetings, Task 6.2 participants kept continuous online communication to finalise the evaluation template, share the progress of the study area reports and to agree on the submission/review process.

Internal submission

It was agreed that the reports will be submitted in phases, in order to avoid review overload. The first part of the evaluation template was submitted for internal review at the end of December, the second half was submitted before the end of February, and the last part was be submitted by the end of March:

- 1st end of December 2018: basic characterization, chapters: Geology of the prospective area; Geophysics of the prospective area; Deep metal enrichment; EGS potential.
- 2nd end of February 2019: advanced evaluation, chapters:
    - Information for CHPM technological elements, incl. Underground heat exchanger (deep metal enrichment + potential reservoir); Production and injection wells; Electrolytic metal recovery and gas diffusion electro-precipitation; Power plant; Salt gradient power generation.
    - Operational characteristics incl. Environmental, social and political background; Financial aspects; Site-specific requirements according to the Grant Agreement
- 3rd end of March: 3D modeling results (Integrated 3D-4D model).

All previous chapters were updated when needed by the end of March. The submission of D6.2 Report on Pilots was in May.

Mitigation measures

During the project review meeting, it has been identified that there is a “The risk of not having enough data and detailed and comprehensive information for the preparation of study areas (WP6), to clearly show the potential of the CHPM2030 technological solution and allow for future advances in the TRL building on the results of CHPM2030, has to be addressed and mitigation measures put in place before end of December 2018”. This is a general risk that was anticipated in the beginning. The established mitigation measures included:

- Developing a study area evaluation template and framework (Lanzarote and Brussels workshops, Cornwall & Romania field trips)
- October 3. online workshop on 3D modelling status and evaluation template qualitative (good, mixed or gaps & recommendations) review of different chapters at each study area.
- Online follow-up meeting with the study areas to discuss the mitigation measures plan, and updated accordingly (Mid December).
- multiphase internal submission and review process of the study area reports (December 31, February 28, March 30), to ensure consistency of the different study area reports.
- Review each part of the documents provided by BGS, IGR, LNEG, and update it before April (January - April).
- Online meeting for the status of the reports, submission timing and review process. (mid-March 2019).
- Identified gaps & recommendations (to be addressed in the roadmap) discussed between the study areas in the online workshop (April 2019).

3.3 Explanation of the chapters in the final evaluation template

The evaluation template outlines the topics that are important to cover when evaluating an area for CHPM potential with the aim to be used as:

- aid for evaluating the study areas;
- guideline for the EFG LTPs for the EU spatial database on prospective CHPM locations;
- assistance and instruction on how to select and assess any other location, beyond the project for the first pilots;
- input for the Roadmap 2030.

The final evaluation template has been finished and circulated within the study area representatives. It contains the 9 chapters.

1) Geology of the prospective area

CHPM geology: description of the local geology in the regional context, but focusing on the target formation.

Including the following aspects:

- local geology (in regional context), tectonic development;
- focus on CHPM target formation;
- interpretation from surface indication to deeper structures;
- interest is originally fractured systems (skarn, VMS, etc.);
- list of available cross sections, geological maps, geochemical results, lithological information and other geological data resources.

Notes: Many of these issues has been described in WP1 and reported in Deliverable 1.2., therefore study areas were asked shortly summarized, update and reference the results presented in D1.2. The same true for the next chapters in the template: Geophysics of the prospective area.

Keywords: local geology, stratigraphy, lithology, cross section.

2) Geophysics of the prospective area

CHPM geophysics: Description of previous geophysical measurements and findings on the area, in CHPM relevance. What measurements can be used and how to locate/define the deep metal enrichment. Presenting available geophysical maps, cross sections, logs, other measurements in the Annex.

- Previous geophysical measurements (in CHPM relevance).
- Geophysical results that can be used for locating/defining the deep metal enrichment.
- List of available geophysical maps, cross sections, logs and other measurements.

Notes: already done in WP1, therefore shortly summarized and referenced to D1.2 and other detailed studies,

Keywords: geophysical data, interpretation.

3) Deep metal enrichment

Mineralization: Description of the (expected) deep metal enrichment based on available geophysical, geological and samples information, geochemistry, etc.

Including:

- Type of mineralization, metals.
- Applicable leaching agents based on WP2.

Keywords: mineralization, deep metal enrichment, applicable leaching agents.

4) EGS potential

EGS Geothermal potential: Description of the EGS potential (heat & energy) of the area; Geothermal characteristics (temperature gradient, heat flux, stress field, thermal conductivity, water availability, EGS geology); Presence of deep fluids/brines, fracture system, crustal permeability. As CHPM is a geothermal technology at its core, the precondition for such application is a functioning geothermal system. At this point the geothermal/EGS potential is investigated through the following points:

- EGS potential (heat & energy) of the area.
- Geothermal characteristics (temperature gradient, heat flux, stress field, water availability, EGS geology).
- Presence/indication of deep fluids/brines, fracture system, crustal permeability.
- Deep water availability.
- Output parameters of the reservoir at the production well.
- Petrophysical parameters.

Keywords: EGS, reservoir, water availability, geothermal energy.

5) Integrated 3D-4D model

Integrated 3D model: from geological and geophysical results compile 3D model of the target area and deep mineralization zone. During the working meetings in WP6, it has been established that an important point for advancing the study area understanding, compared what has been delivered in WP1, is the development of an integrated 3D, potentially 4D model. This could be a major advancement compared to what has been presented in WP1 Deliverable 1.2. Developing new 3D model would be the answer to the initial core question of Task 6.2: How can we advance the study area evaluation from the solid baseline which has been already provided in WP1?

- 3D integration of geological and geophysical results.
- Already existing 3D-4D models of the target area and the deep metal enrichment.
- Integrate all available “geo” data into existing/new 3D/4D model for better understanding the picture as a whole, to help the deeper extrapolation, for better conceptual understanding, test the theories we have from the area, visualize data, create new and tangible results of the area.
- The model ideally includes geological structures, mineralization, hydrogeological flow, stress field, reservoir and hydrodynamical parameters, fluid losses, etc.

Notes: CHPM2030 is a TRL4-5 research project and the first pilots are set for 2030, therefore, it is not expected to deliver fully developed, “commercial” 3D models by the end of the project. The goal is to set the direction, create the first models and tackle the remaining gaps with structured recommendations in the Deliverable 6.3 Roadmap 2030 document.

Keywords: 3D modelling, visualization, interpretation, depth continuation, deep metal enrichment.

6) Information for CHPM technological elements

The following subchapters are focusing on the CHPM technological components and describes the available information regarding each study areas. These are the expected range of parameters at the future CHPM building blocks: underground heat exchanger, production wells, electrolytic metal recovery, heat exchanger, gas diffusion electro-precipitation, salt gradient power generation and injection wells (based on D2.4 Overall system dynamics). Environmental mitigation strategies, social and political background, financial aspects are also considered here.

For future pilots, all these aspects required to be fully described and elaborated. However, due to current knowledge gaps and limitations, actions and recommendations are going to be formulated to reach that level of understanding at the study area in the future. These next steps will be summaries in the Deliverable 6.3 Roadmap 2030 document.

6.1) Underground heat exchanger (deep metal enrichment + potential reservoir)

- extension of the metal enrichment (volumetric interpretation);

- expected type and porosity/permeability (fractured, porous, etc.) of the reservoir;
- type of mineralization and expected metals.

Keywords: mineralization, reservoir.

6.2) Production and injection wells

- depth of potential wells;
- conceptual drill and well design (based on the stress field and the area specifics);
- wells connection;
- expected temperature/pressure at the bottom/wellhead.

Notes: on a conceptual level, what can we expect for these aspects.

Keywords: Drilling depth, well design.

6.3) Electrolytic metal recovery and gas diffusion electro-precipitation

- potential target metals/products to be recovered;
- brine: foreseen chemical composition and physical parameters.

Keywords: target metals, potential products.

6.4) Power plant

- local heat and electricity demand (industrial, municipal, agricultural, etc.);
- access to the grid.

Keywords: demand for heat & electricity, grid availability.

6.5) Salt gradient power generation

- salinity of expected geothermal brine;
- fresh water supply from the surface (water sources).

Keywords: fresh water supply, brine salinity,

7) Operational characteristics: Environmental, social and political background

Environmental:

- list of potential environmental risks and mitigation strategies (gaseous and solids emissions, water and noise pollution, induced seismicity, land use/subsidence, induced seismicity/landslides, water use, thermal pollution, etc.);
- in-line with D2.4 and WP5 integrated environmental assessment;
- local competition for land and water availability;
- risk of mobilizing radioactive/toxic materials.

Social**:**

- Social Licence to Operate,
- public acceptance for geothermal applications.

Political:

- political support on renewable/geothermal energy:
- licensing: how to get the licence for the technology, it can get difficult;
- presence of supporting legislation, regulatory framework.

Notes: Due diligence, de-risk a project before the start.

Keywords: environmental risks and mitigation strategies, SLO, licencing.

8) Financial aspects

Financial aspects: applying the financial tools developed in WP5. Local demand for heat (green houses, industry, residential, greenhouses, illustrated with Lindal diagram, etc.) and electricity (proximity of electric grid, residential/industrial needs etc..).

- Use of economic tools developed in WP5 (shifted to the roadmapping document).
- List of potential local stakeholders (community, political, companies).
- Local demand for heat and electricity.
- Potential investors.

Keywords: WP5 financial tools, local investors, geothermal energy utilization/demand.

9) Site-specific requirements according

Is has been also agreed to include specific site-specific aspects, outside of the evaluation template, at the end of the report. Each study area interpreted and summarized these issues shortly according to the Grant Agreement, while the evaluation template covered the larger picture.

Considering that CHPM2030 is a research project at TRL 4-5 and the first pilots are set for 2030, this template is not expected to be completed with all details and aspects of the presented topics. This is not possible at the moment, mainly due to lack of data from CHPM target depth. Instead, the template is to set a common framework and direction to evaluate the study areas according to the available data, collected in WP1, and then tackle the remaining gaps with structured recommendations, that can be fully elaborated in Deliverable 6.3 Roadmap 2030 and 2050. Some of the topics, such as social, political, environmental background, therefore are covered with short qualitative reflection, ensuring that all important aspects are considered.

4. Executive summaries of the study area reports

4.1 South West England

Full report in Appendix 6.2.1: Report on Pilots: South West England. Authors: Paul A J Lusty, *Principal Economic Geologist*, Richard B Haslam, *Structural Geologist*, Richard A Shaw, *Economic Geologist*, Eimear A Deady, *Minerals Geoscientist*, Paul Williamson, *Senior Geophysicist*, British Geological Survey.

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

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

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

This review whilst considering the broader scale geological context, principally focuses on a study area covering the northern part of the Carnmenellis granite, one of the six exposed granite plutons that form the Cornubian Batholith. At surface the Carnmenellis granite is roughly circular in shape and covers an area of some 135 km2. However, in common with the other plutons its shape at depth and thickness remains uncertain. This project used borehole data in conjunction with existing gravity models to better constrain the position of the upper granite surface.

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

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

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

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

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

Cornish granites typically have very low primary permeability, but relatively high hydraulic conductivity as a result of faults and joints. The latter are particularly important for controlling fluid flow in Cornish granites. Fluid circulation has been a continuous feature of the Carnmenellis granite and its host rocks since emplacement. Fluid circulation is evident in the local mines where thermal, saline brines discharge from crosscourse structures. It is concluded that a dynamic system driven by convective and hydrodynamic forces has allowed continuous water-rock reaction to occur within the upper 3–4 km of the currently exposed pluton. It is thought that a large reservoir of probable diluted palaeobrines exists at depth in this area. However, these are not viewed as static, trapped palaeofluids, but rather part of a dynamic system of fluid circulation, involving continuous mixing of saline and meteoric waters, and water-rock reaction that continues today. These brines contain lithium concentrations of up to 125 mg/l^{-1}, probably as a result of the mica breakdown during fluid-rock interaction.

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

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

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

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

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

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

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

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

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

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

4.2 Iberian Pyrite Belt, Portugal

Full report in Appendix 6.2.2: Report on Pilots: Portugal, Iberian Pyrite Belt. Authors: Elsa Cristina Ramalho, *Geological Engineer*, João Xavier Matos, *Economic Geologist,* João Gameira Carvalho, *Geophysicist*, Portuguese National Laboratory of Energy and Geology.

This report provides an update of geoscientific data and information relating south-west Iberian Pyrite Belt (IPB), Portugal. The IPB massive sulphides deposits is a Variscan metallogenic province located in the SW of Portugal and Spain that hosts the largest concentration of massive sulphide deposits worldwide, covering about 250 km long and 30–50 km wide and are associated with volcano-sedimentary sequences present in sea floor environment (http://geoportal.lneg.pt). This geographical area, with particular geological volcanic and sedimentary sequences of Carboniferous and Devonian ages, identified in the southwest of the Iberian Peninsula runs from NW to SE, from Alcácer do Sal (Portugal) to Seville (Spain), and, in the Portuguese side, it covers two active mines: Neves-Corvo mine, owned by Lundin Mining (www.lundinmining.com), and at the Aljustrel mine, owned by Almina (www.almina.pt). For its potentialities and full mining operation with good prospective of increasing in depth the research and exploitation, Neves-Corvo Mine was chosen for test site, to be studied for CHPM purposes, because of its depth of exploitation and undergoing research projects (SmartExploration and Explora UE projects). Because of these projects a deep 3D geological and geophysical model is being reviewed, with old mining data and recent acquired geophysical acquisition, reprocessing and reinterpretation. At the same time, its relation with EGS potentialities will be considered. The Neves-Corvo mine area includes presently 7 massive sulphide ore lenses and is mainly a copper and zinc mine, producing copper, zinc and lead concentrates. The operation is owned and operated by Lundin Mining's Portuguese subsidiary Somincor (http://www.lundinmining.com). Although this mine does not explore any ultra-deep orebodies that allow the application of the CHPM technology yet, prospecting in depth is underway to check for the continuity of the Lombador orebody, so far. Lombador is the deepest orebody that is identified in the Lundin permit area. Geophysical modelling and reflection seismics were conducted under the scope of H2020 SmartExploration (H2020) (https://smartexploration.eu/) and Explora (Alentejo2020) projects and a more refined model will turn out with the available data.

This report will cover the main parameters regarding the feasibility of the implementation of the CHPM technology in Neves-Corvo, that will complement the CHPMD1.2.2. report, namely in the possibility of existence of ultra-deep boreholes in the future and in the geothermal gradient that allows reaching adequate temperatures to produce energy (~70 °C) at relatively shallow depths (~2.5-3 km), compatible with both energy production and metal recovery in the geothermal brine to increase mining production.

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

Finally, some new data is incorporated into a GoCad 3D model as an update to the GoCad model published in ProMine (EU FP7, Carvalho et al., 2016). This update includes supplementary information, such as deeper and all other recent boreholes information, from 2012 to 2018, to cross-check with geophysical data, reprocessed gravimetric, magnetic, electromagnetic and surface and deep reflection seismic data.

4.3 Beuis Basin, Romania

Full report in Appendix 6.2.3: Report on Pilots: Romania. Authors: Diana Perșa, *Researcher*, Ștefan Marincea, *Senior Researcher*, Delia Dumitraș, *Senior Researcher,* Cătălin Simion, *Researcher*, Geological Institute of Romania.

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

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

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

Both North Apuseni Mountains and Bihor Mountains have the following characteristics:

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

Geothermal potential

For the eastern limit of the Pannonian Basin, Rădulescu and Dimitrescu (1982) estimated the mean heat flow of 96 mWm-2. Geothermal gradients for Pannonian Basin are high, varying from 6.2 to 5.6 ^{0}C/100 m at 500 m and at 2000 m b.s.w.l respectively. Due to the thin crust and the thin lithosphere, Beiuș Basin is characterized by high heat flow, with values up to 90 mWm-2.

In Apuseni Mountains, in areas affected by Tertiary tectogeneses usually referred to terrains younger than 50 Ma, the three components of the regional heat flow: crustal radiogenic, thermal transient perturbation, and background heat flow from deeper sources, contributes with 36, 27 and 27 mWm^{-2}, respectively, to the mean value 90 mWm^{-2}.

Thermal conductivity [10-3cal/cm x ^{0}C x s] of the rocks belonging to the Romanian part of the Pannonian Basin and the surrounding areas has been determined through laboratory methods, and has high values varying from 3,5 – 12 for granites, 4.8 – 5.0 for diorites and 6 – 7 for dolomitized limestone.

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

Deep metal enrichment

Mineralization is widespread in the mountainous area and is expected to be found in the basin area. In Bihor Mountains the mineralization is generated during the banatitic calcalkaline magmatism (Post-Lower Masstrichtian-Palaeogene), which is represented by bodies of intrusive rocks, generally hypabyssal as well as plutonic ones, which are widely developed in the depth. Plutons of granodiorite-granite rocks, to which the main sulphide mineralization is genetically linked, constitute main mass of banatitic bodies in the Apuseni Mountains; in Bihor Mountains they crop out on small areas, but they develop in the depth.

Magmatic bodies intruded Permian-Mesozoic sequences and produced contact-metamorphic aureoles, at Pietroasa, Budureasa and, most extended at Baita Bihor. In the contact aureoles of the granodiorite-granites plutons, skarns with Fe, B, Bi, Mo have been formed. At Valea Seacă, Valea Mare-Budureasa etc., the skarns are overlapped by sulphide mineralization.

Brucite deposits from Budureasa and Pietroasa were investigated by surface pits, drillings and underground galleries. They have been formed at the contact of granodiorites with the Anisian dolomites and have a structure with four zones, ranging from granodiorites to pure dolomites containing holocrystalline hypidiomorphic granodiorites, magnesian skarns, Brucite-bearing zones, recrystallized Anisian dolomite.

Borate deposit is situated in the middle basin of the Aleului Valley (Bihor Mountains), at its confluence with the Sebisel Valley, at the Gruiului Hill. The formation of the borates from the contact aureole of the Pietroasa granitoid body is the result of an infiltration metasomatic process.

W-bearing and base metal skarns are characteristic only for Baita Bihor. At Baița Bihor, some magnesian skarn bodies or ore pipes such as those at Antoniu, Bolfu-Tony, Hoanca Motului, Baia Roșie are boron-bearing skarns and represents well-defined metasomatic columns. A sole similar body, or metasomatic column, that from Dealul Gruiului was identified at Pietroasa.

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

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

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

3D model

Integrating all the data available in a 3D geological database and creating the 3D geological model provided an overview on the spatial distribution and the geometry of the middle and upper Triassic sedimentary deposits within Beiuș Basin and their contact with the Upper-Cretaceous intrusive body, from Bihor Mountains.

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

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

The 3D model emphasizes the large areas on which Triassic deposits outcrop. Being represented by highly fissured karst deposits they, on one side, assure a continuous recharge of the geothermal aquifer, but, on the other side, they have an important contribution to the decrease of the geothermal potential of the rocks, being a cooling agent.

The batholith's apophyses that were detected by complex geophysical methods within Beiuș Basin, and can be taken into consideration for further investigations are represented by the model.

The 3D model helped to visualize and understand the spatial relations at the border between the basin and the mountains and provides new data that are needed to set the parameters for planning new exploration works.

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

Hydrogeology

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

Geothermal district heating system

Beiuş town has an extensive geothermal heating system (GDHS), which provides heat for approximately 70% of the population, covering about 60% of the urban heating demand. The previous system that used coal as a source of energy was completely replaced by GDHS. The geothermal heat energy is delivered to the consumers either indirectly via substations with heat exchangers feeding double closed loop distribution pipe networks, one for Domestic Heating (DH) and the other for Hot Sanitary Water (HSW), or directly to the individual buildings with their own heat exchangers. The exploitation license of Beiuș geothermal reservoir perimeter is owned by Transgex S.A.

In 2016 the energy of 74,452 of GJ/year has been delivered to the population. The value of water production was higher than 1 million m3. In 2018 a partnership formed by the City Hall and private company submitted project proposals in order to get EU funding for the extension of the GDHS. They also showed their interested for the results of CHPM2030 project and expressed their will to be part of a consortium that could consider a CHPM installation in Beiuș in the future.

4.4 Nautanen, Kristineberg, Sweden

Full report in Appendix 6.2.4: Report on Pilots: Sweden. Authors: Gerhard Schwarz, *Geophysicist*, Benno Kathol, *Geologist,* Magnus Ripa, *Geologist*, Bo Thunholm, *Hydrogeologist* Edward P Lynch, *Geologist,* Johan Jönberger, *Geophysicist*, Geological Survey of Sweden.

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

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

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

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

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

The Geological Survey of Sweden has a long-standing tradition in geological mapping of the country with the support from airborne geophysics, motivated by the low degree of bedrock exposures. Magnetic properties, electrical resistivity and gamma radiation of shallow crustal rocks were thus studied in the Skellefte district and the Nautanen area, complemed by ground surveys on these rock properties and on gravity.

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

The Nautanen deposit is situated in the Northern Norrbotten ore province in northernmost Sweden. At this historical mining location, intermittent exploration has been carried out for over 100 years. Approximately 72 000 tonnes of copper and iron ore were extracted between 1902 and 1907. Further exploration in the 1970s and 80s produced a pre-regulatory total resource estimate for the "old" Nautanen deposit of approxi¬mately 2.94 Mt grading 0.78%

Cu and 0.52 ppm Au. Present-day exploration by Boliden Mines ral AB has resulted in the discovery of an additional copper-gold mineralisation approximately 1.6 km north-northwest of the old Nautanen mine along the trend of the Nautanen deformation zone (NDZ). This “Nautanen North” deposit has an indicated resource of 9.6 Mt grading 1.7% Cu, 0.8 ppm Au, 5.5 ppm Ag and 73 ppm Mo, with an additional inferred resource of 6.4 Mt grading 1.0% Cu, 0.4 ppm Au, 4.6 ppm Ag and 41 ppm Mo.

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

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

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

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

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

5. Extended summary of European Prospective Locations

Full report in Appendix 6.2.5: Report on European Prospective Locations. Authors: Domenico Marchese, *Project Officer*, Anita Demény, *Project Officer*, Isabel Fernandez, *Executive Director*, European Federation of Geologist

This work has put together the data collected with the results of the most recent predictive metallogenical models. The report provides a "European perspective" on the potential areas of CHPM development.

The Linked Third Parties, following the guidelines and indications provided by the European Federation of Geologists, have evaluated the existing geological data relating to mineral formations and geothermal projects, previously collected in WP1 (Work Package), according to the potential application of CHPM technology. This work has put together the data collected with the results of the most recent predictive metallogenical models.

The task of the LTPs were three-fold:

1. Area selection: this task was concerning with the selection of a limited number of sites where drill holes showed the entry characteristics to define an area most likely to be a future CHPM candidate (Temperature, Metal enrichments, fluids, etc.).
2. Basic area evaluation: the task continued with the evaluation of the basic characteristics of the selected areas by taking into account geological and geophysical data with a CHPM relevance, mineralisation, integrated 3D models, EGS potential info and so forth.
3. CHPM characteristics: this task considered a deeper investigation and data comprehension of the most likely CHPM candidate sites where some operational characteristics and well capacity were taken into account as well as the related environmental and social impacts that may arise from such CHPM systems.

The area selection was a screening process, looking for areas for future CHPM application, that is intended to be further investigated in the future, as interest for CHPM technology arise. Areas selected as type B, has the potential for metal extraction and direct heating systems (“CHM”), while areas type A has the potential for heat, power and metal extraction (”CHPM”). In either case the next step if further geophysical/geological exploration at the identified areas.

16 of the LTPs have been involved in the task, investigating CHPM potential in the following countries: Belgium, Czech Republic, Finland, France (investigation conducted by EFG), Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Serbia, Slovenia, Spain, Switzerland, Ukraine. Besides, the "Institut Royal des Sciences Naturelles de Belgique" (IRSBN), collected and evaluated the data provided by 8 other countries that were not directly involved in the Project (e.g. Austria, Croatia, Cyprus, Luxembourg, Slovakia, Sweden the United Kingdom).

As a summary, 34 over 50 places have been identified with “Type A = T>100°C” and more than 22 with "Type B = T>40/50°C", that have future potential for applying CHPM technology in the future. In the selected areas several kinds of mineralisation have been identified: Hydrothermal, Epithermal and Porphyry are those most commonly reported. The depth of mineralisation, as well as the correspondence temperature, vary considerably site by site (exhaustive reports of each selected site have been collected in Annex where the reader may find a list of commodities and the degree of mineralisation expressed in % or ppm when provided by the LTPs).

The study has supported the development of a spatial database of European prospective locations for CHPM technology. The data collected on a European Scale was delivered on the web-based interactive platform, with OpenStreetMap (OSM). All the outputs, visualised in the spatial database, have been made accessible to the public: http://bit.ly/CHPMinfoplatform.

6. Conclusions

Task 6.2 objective of setting "the ground for subsequent pilot implementation", has been completed by the 1) development of a common evaluation template, that facilitated the investigation of the study areas according to the consortium's common understanding; 2) evaluation of five European study areas: SW England, IPB, Romanian Beius area, Sweden (Nautanen, Kristineberg), according to the harmonised evaluation template; 3) creation of a European outlook on prospective location, including a publicly available spatial database.

The baseline for this study was developed in WP1, Task 1.2 Knowledge gaps and updating information. In CHPM2030 Deliverable 1.2 Report on Data Availability (Schwarz et al. 2016) a brief overview was presented about the four major ore districts in Europe: SW England, Southern Portugal, NW Romania and Central and Northern Sweden. Beside these focused reports, a trans-European inventory was also created of drill holes where temperature exceeded 100 °C and metal enrichment was encountered. Here the focus was on data availability, whereas in Task 6.2 the focus was on the detailed evaluation of data.

In Task 6.2 the first activity was the development of a harmonised study area evaluation template. This guideline was created with the involvement of the entire consortium, through workshops (Lanzarote study area workshop with the consortium: 22-23 March 2018, Brussels workshop with the Linked Third Parties: 12 April 2018), online meetings and fieldtrips (Cornwall field trip: 22-24th of May 2018, Romania field trip: 25-26 July 2018). This was an iterative process with the involvement of the technology developers and the study area representatives.

The final evaluation template outlines a group of important topics that must be taken into account when evaluating the CHPM potential at a given area. The topics are the following:

Geology and geophysics of the prospective area, Deep metal enrichment, EGS potential Integrated 3D-4D model, information for CHPM technological elements (underground heat exchanger (deep metal enrichment + potential reservoir), Production and injection wells, Electrolytic metal recovery and gas diffusion electro-precipitation, Power plant, Salt gradient power generation), Operational characteristics (environmental, social and political background, financial aspects), with numerous subtopics and a short description.

The evaluation guideline is to be used as 1) an aid for evaluating the study areas; 2) a guideline for the EFG LTPs for the EU spatial database on prospective CHPM locations, 3) assistance and instruction on how to select and assess any other location for the first pilots; 4) input for the Roadmap2030.

Now that all available information, provided in D1.2, has been updated and evaluated (D6.2) for CHPM potential, the next step is to plan ahead and see what actions needs to be done, in order to arrive to pilot readiness level by 2030, in the form of a roadmap.

The roadmapping activity for CHPM aims to directly support the early implementation of the technology at the pilot sites, follow-up on the technology components, and the definition of how overall geothermal technology may evolve. These aspects may be developed together, but given the current available resources, it is split to three actions corresponding to the three layers of the D6.3 Roadmap for 2030 and 2050 document.

Part 1 is the continuation of WP6 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.

- → Testing the overall CHPM concept
- Input from Roadmapping workshop in Las Palmas
- Output: actions and timeline for reaching the vision described in D6.1.

Part 2 is going to be the direct follow-up of the technological components, with the contribution from the responsible partners, providing short-, mid- and long-term research plan. This includes a one paragraph description of the current state-of-the-art, immediate research plan, mid-term (2030) requirements for pilot readiness level (TRL 6-7), and long term (2050) objectives for the commercial level (TRL 8-9) application, for each technological component: Integrated reservoir management, Metal content mobilisation using mild leaching and with nanoparticles, GDEx, HPHT electrolytic metal recovery, Reverse osmosis electrodialysis, System integration. This aspect gives concrete guidance and direction at the technology component level.

- → Testing the current CHPM schematics,
- Input from the CHPM component follow-up roadmap,
- Output: the State-of-the-art, Immediate research plan, Pilot research plan (2030), Long term objectives, goals (2050), for the current CHPM components.

Part 3 is dealing with the study areas, giving instructions, needs, exploration plan for the next 10 years about how to arrive to pilot readiness level or to actual pilots by 2030, based on the gaps and recommendation, identified during T6.2. This part aims for direct support for the first pilot to be implemented at the study areas.

- → Testing the potential areas for applying current CHPM concept,
- Input from the study area roadmapping online meeting in early May and study area reports,
- Output: actions, needs, exploration plan, agenda, for the next 10 years' timeline, in order to reach pilot readiness level or first "CHPM plug-in" ready pilots.

All CHPM2030 study areas had very different geological, geothermal and mineral characteristics. This provided a complementary coverage of the type of areas that may be of interest in Europe for the future. However, due to the same reason, the reports reached different levels of maturity, and the recommendations, to be formulated as part of the roadmap, are also going to be specific for the individual areas.

The report on south-west England, considered the availability of geoscience information, the geological environment, geothermal characteristics, potential for deep metal enrichment, and technical, environmental, social and regulatory factors that could influence the future development of CHPM extraction technology in the region. Preliminary modelling of the

Cornubian Batholith has been undertaken to improve understanding of its properties relevant to geothermal energy development. A regional model was constructed to understand the spatial relationship of key geological parameters. This data was used for the development of two site-scale models that aimed to improve understanding of the fracture network and flow pathways at the reservoir-scale. In summary south-west England, and specifically Cornwall, is an excellent location for a pilot-scale CHPM system. It has the essential prerequisites of a proven geothermal energy resource and abundant polymetallic mineralisation. It is one of the best surveyed and most data-rich parts of the UK, with a long history of mineral development and geothermal research. The local government and communities appear supportive of deep geothermal resource development, and it has a major, active co-funded deep geothermal project.

The report from Portugal provides an update of the geoscientific data and information on the South-West Iberian Pyrite Belt (IPB), a Variscan metallogenic province with massive sulphides deposits. This active mining region, with vast amount of geological information available, has a good prospect of mineralization at deeper levels, therefore of interest for CHPM technology. The chosen study area is Never-Corvo Mine due to the available 3D geological, geophysical models and its relation with EGS potential. The deposit consists of 7 massive sulphide ore lenses with copper, zinc, and lead mineralisations. The report presents the relevant geological, geophysical, mineralogical characteristics of the area to investigate the feasibility of the implementation of CHPM technology at Never-Corvo. The main interest is the existence of the deep mineralization, near the operating mine. The coproduction of energy and minerals would extend the lifetime of the mine operation. The study also presents emerging factors, such as the energy transition, financial requirements and possibilities, advancement in 3D modelling of the deposit, challenges to generate data about the deeper levels (>1.2 km), environmental, social and political background, and the possible future agreements between the mining management and the Portuguese government. There was also a synergy with the ongoing mining operations, parallel EU funded projects (SmartExploration, Explora), and the CHPM study are evaluation.

At the Romanian study areas, the Beius basin and the Bihor Mountains were investigated by IGR due to the favourable geothermal and mineral potential of the areas for CHPM technology. In the Beius Basin, the geothermal potential is high due to the thin crust, as a result of a regional extension in the Pannonian Basin, resulting high heat flow (above 80mW/m^2) and elevated geothermal gradient (5.6-6.2 ^{o}C/100 m). Deep mineralization is also expected due to intrusive magmatic bodies within the Beius Basin. On the other hand, the Bihor mountains are also of interest due to the mineral deposits, which is part of the Banatitic Magmatic and Metallogenetic Belt metallogenic province. The granodiorite – granite plutonic body, formed skarn mineralization at the contact with Mid- and Upper Triassic limestones. The identified deposit types of interest are 1) iron, boron, bismuth, molybdenum bearing skarns, and related vein occurrences with copper, zinc, lead sulphides, 2) Brucite deposits from Budureasa and Pietroasa, 3) Borate deposit from the contact of aureole of the Pietroasa granitoid body through metasomatic processes, 4) wolfram bearing and base metal skarns at Baita Bihor. Furthermore, there is an ongoing district heating system in Beius town, whose operator showed interest for the CHPM technology in the future. This shows public support for geothermal applications, indicated geological potential for heat and metals, and industry interest for the additional metal extraction technology.

In Sweden, two CHPM test sites are proposed for further investigations: These are the Kristineberg area in the Skellefte district and the Nautanen area in the Northern Norrbotten ore province. The Kristineberg area is known for its volcanogenic massive sulphide deposits (VMS). Zinc is the main target, though in some areas copper and gold ores are mined. The area was studied by geophysical methods down to 12 km and by drilling down to about 1400 m below surface. High resolution reflection seismic data outlined the VMS ore bodies and associated structures. However, the completed seismic surveys also have shown that considerable efforts were needed to acquire high quality data, preferably by 3D surveys. The operations in the Kristineberg mine have reached a depth of 1200 m, 31 million tons of ore were mined, reserves are 5 million tons and resources about 13 million tons. The combined grades of mined ore, reserves and resources are 3.9 % zinc, 0.7 ppm gold, 44 ppm silver, 0.9 % copper and 0.4 % lead. Mineralisations in the Nautanen area are part of several hydrothermal copper-gold occurrences related to the ironoxide-copper-gold (IOCG) mineral deposits. The “Nautanen North” deposit has an indicated resource of 9.6 million tons of ore grading at 1.7 % copper, 0.8 ppm gold, 5.5 ppm silver and 76 ppm molybdenum, with additional inferred resources of 6.4 million tons grading at 1 % copper, 0.4 ppm gold, 4.6 ppm silver and 41 ppm molybdenum. In both mining areas, the installation of a CHPM system is highly challenging. The low geothermal gradient of only about 16 ^{o}C/km and heat flow density of about 50 mW/m^2, typical to the Fennoscandian Shield, demand large borehole depths of at least 5 to 7 km. At such depths, there is very limited information available about geological structures, deep-seated fluids, and hydraulic conductivity of the crystalline bedrock. However, with the help of integrated geophysical studies, i.e., deep seismic and magnetotelluric measurements and in cooperation with the mining industry, many advancements were made facilitating the CHPM potential in future projects.

The European outlook for prospective CHPM potential has been prepared with the help of the EFG's Linked Third Parties, the national geological associations. In total there were 24 countries covered: Belgium, Czech Republic, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Serbia, Slovenia, Spain, Switzerland, Ukraine, Austria, Croatia, Cyprus, Luxembourg, Slovakia, Sweden the United Kingdom. In each country, there were 3 tasks: 1) Area selection: define an area most likely to be a future CHPM candidate; 2. Basic area evaluation: the task continued with the evaluation of the basic characteristics of the selected areas; 3) CHPM characteristics: this task considered a deeper investigation and data evaluation of the most likely CHPM sites. This was a rough screening for areas that may be further CHPM site. Areas selected as "type B", has the potential for "CHM" technology and use the delivered metal extraction technological couples with direct heating application. Areas selected as "type A" may be actual areas for a full scale CHPM application, after a thorough geophysical exploration that can show the ultra-deep mineral enrichment. This work has shown a number of areas that has potential to develop a CHPM site, but the lack of publicly available data may still represent a bottleneck to improve the knowledge needed implement CHPM technology at any of the selected sites. The identified areas have been gathered in a publicly available online database: http://bit.ly/CHPMinfoplatform.

It has been found that a new type of exploration mindset is required for undertaking such survey. Exploration at areas for combined heat, power and metal extraction will have to use the traditional surveying and interpretation methods, but it must improve on them, and combine tools from both geothermal and mineral exploration campaigns, to create a comprehensive strategy. The first step for that was the creation of the evaluation template, which served as a "checklist" for important characteristics to consider when looking into

CHPM potential. The 5 study areas from 4 countries have been evaluated according to this new strategy and each area has the potential to develop actual CHPM pilots in the future. Each area has its unique characteristics, but overall, they all have substantial amount of information available publicly from the top 1 km of the crust, providing a good understanding of the near surface. The next challenge thus is to extend this understanding at deeper levels, run new, preferably 3D surveys, further advance each predictive 3D models for a downwards continuation. With the help of these study reports and the European outlook study, the following items have now been clarified: 1) the information available at each area, 2) the CHPM potential based on this geoscientific data, 3) remaining gaps to be overcome in the future. Based on this knowledge, the idea of pilot implementation can be further advanced through concrete recommendations in the CHPM2030 roadmaps (CHPM2030 Deliverable 6.3). The next exploration/research projects can continue, based on these recommendations and the CHPM pilot readiness level can be achieved by 2030.

References

Gerhard Schwarz, Magnus Ripa, Bo Thunholm, Richard A Shaw, Keith Bateman, Eimear Deady, Paul Lusty, Elsa Cristina Ramalho, João Xavier Matos, João Gameira Carvalho, Diana Perșa, Ștefan Marincea,, Albert Baltreș, Constantin Costea, Delia Dumitraș, Gabriel Preda, Vanja Bisevac,, Isabel Fernandez, 2016: Report on data availability, CHPM2030 project Deliverable D1.2, link:

https://www.chpm2030.eu/wp-content/uploads/2017/02/CHPM2030_D1.2_public_small.pdf

List of Appendices: Report on Pilots

A6.2.1: Report on Pilots: South West England.

A6.2.2: Report on Pilots: Portugal, Iberian Pyrite Belt.

A6.2.3: Report on Pilots: Romania.

A6.2.4: Report on Pilots: Sweden.

A6.2.5: Report on European Prospective Locations.