Towards Conceptual-Model Based Exploration and Appraisal of Geothermal Resources: The FindHeat Project

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Summary

To enable reliable exploration strategies for geothermal energy that have inherently lower economic and technical risks and hence increase public support, the multi-national, multi-disciplinary, and publicly funded FindHeat project is developing a novel, conceptual model-based geothermal exploration workflow. This workflow specifically focuses on faster turnaround times for exploration and appraisal of geothermal resources, making better use of legacy data and non-invasive geophysical techniques, and constraining uncertainties with respect to the size of the heat source and the range of possible heat production rates. Comprehensive social science research complements the technical work to set the foundation for new communication strategies that allow geothermal operators to earn the public trust that improved geothermal exploration and appraisal will lead to a more efficient and sustainable exploitation of geothermal energy. The workflow is being tested and validated at eight geologically diverse geothermal plays situated in Iceland, France, UK, Spain, and Netherlands, which allows us to demonstrate its economic and technical benefits as well as its societal impact.

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Introduction

Geothermal energy can provide local and climate-friendly energy for heating and electricity production at a consistent baseload, independent from wind and solar. Successful geothermal projects require favourable geological conditions, namely high temperature and high permeability. However, knowledge where these conditions can be exactly found in the deep underground (up to 5 km) is limited. This is the fundamental challenge. The exploration phase is hence mission-critical: while it is desirable to increase geological knowledge of the subsurface by acquiring additional geological and geophysical data (e.g., 3D seismic surveys), this takes time and often comes at a cost that is too high. Yet, the largest economic risk is directly tied to the exploration results because they influence major investment decisions (10s to 100 M€) about where to drill wells and how to design power plants, without knowing for certain that the wells will yield the expected flow rates and temperatures.

A sustainable business model for geothermal energy requires a high success rate for the development of geothermal projects, which is fundamentally different from oil and gas projects where many low-producing wells are still profitable. Moreover, public perception of geothermal energy is often negative and support for developing this energy source is low. On the one hand, geothermal projects that failed economically were often underwritten by public finances. On the other hand, well-publicised issues like induced seismicity were encountered during the development of some geothermal resources. Both have undermined public trust in the affected communities and beyond, casting doubts on whether geothermal energy can be developed safely and sustainably while addressing local public concerns. These two challenges must be overcome to unleash the full potential of geothermal energy and achieve national and international targets for growing the deployment of geothermal energy.

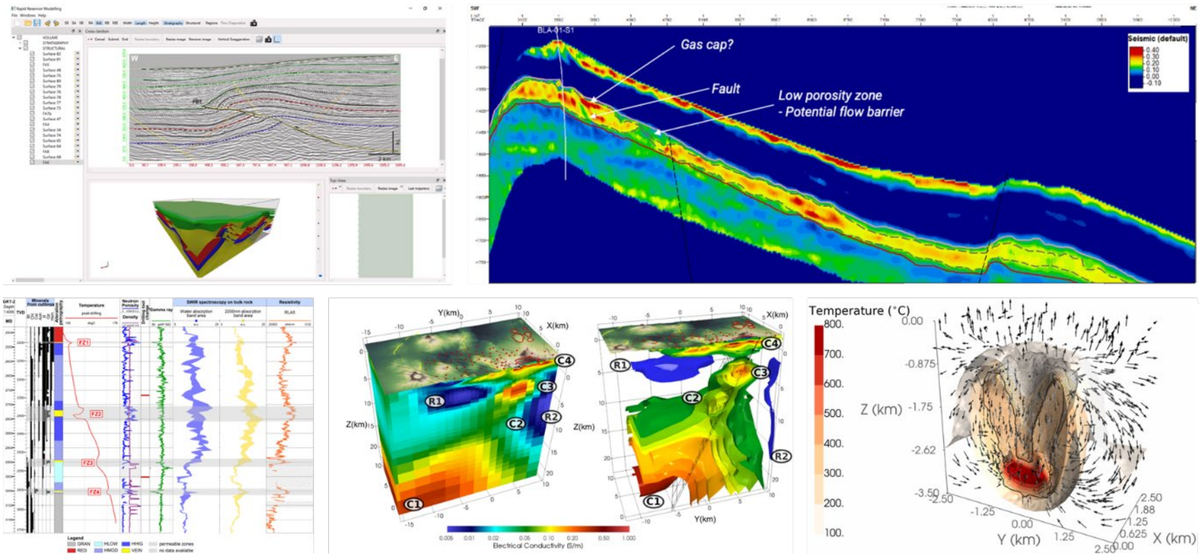

Figure 1. *Examples of the FindHeat technologies: RRM for the fast generation of 3D geological concepts and models in data poor environments (top left), WEB-AVO to improve the illumination of legacy 2D seismic data (top right), SWIR to classify minerals from drill cuttings and identify fracture and inflow zones in wells (bottom left), EMT to analyse the thermal alteration mineralogy and the heat source for magmatic geothermal systems (bottom centre), and numerical simulation results showing temperature distributions in a super-hot geothermal system (bottom right).*

Methodology and Technology Development

The FindHeat project aspires to provide a shift in geothermal exploration towards geothermal resource and exploitation concepts that have inherently low technical and economic risks, i.e. have a low likelihood to encounter induced seismicity and high likelihood to encounter sufficiently high production rates and temperatures.

To achieve this aspiration, technologies are being leveraged that have been successfully applied in other subsurface applications (e.g., CO_2 storage, hydrocarbon production), others are completely new and await testing in geothermal applications (Figure 1). For example, FindHeat utilises a new inversion technique for legacy seismic data, the Wave Equation Based inversion (WEB-AVO). WEB-AVO yields the elastic and rock properties that are needed to develop geological concepts that guide the exploration, appraisal, and development of geothermal reservoirs (Korevaar et al., 2021). By radically improving the information content of legacy seismic data, the need for conducting expensive and disruptive seismic surveys is significantly reduced. Electromagnetic tomography (EMT) methods are being applied to image the electrical conductivity distribution in the subsurface. Electrical conductivity is sensitive to the presence of fluids, temperature gradients, and conductive phases such as hydrothermal alteration products. EMT has been demonstrated to enhance well-location identification in geothermal systems (Samrock et al., 2023) but has virtually no environmental footprint, requires short recording times, and is low-cost. Other non-invasive geophysical techniques such as drone imaging and short-wave infrared spectroscopy (SWIR) are being tested as well. Drone surveys provide imagery of fault patterns and thermal signatures above and in the vicinity of the geothermal reservoir. While successfully applied to high-enthalpy geothermal reservoirs before (Mueller et al., 2022), FindHeat is testing and calibrating the surveys in low- and medium-enthalpy systems and close to operating geothermal plants. SWIR measures adsorption bands for different minerals in drilling cuttings from which specific minerals can be identified (e.g., illite) that serve as proxies for the damaged and altered zones associated with existing (natural tectonic) fractures (Vidal et al., 2019). Compared to traditional temperature and televiewer logs, SWIR is cheaper, faster, can be performed during drilling in poor well conditions.

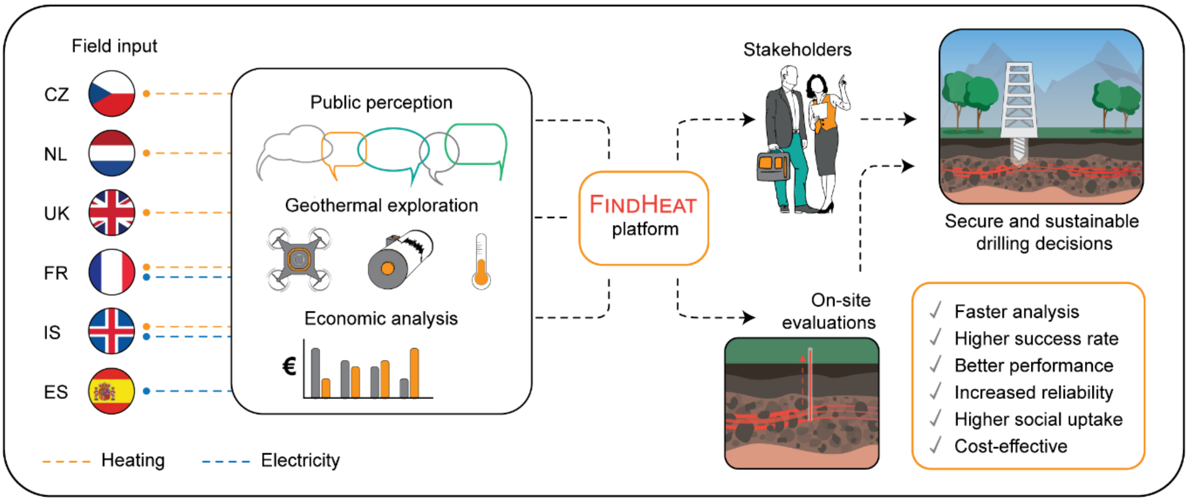

Figure 2. *Concept of the FindHeat project: Novel approaches to collect and interpret geological, geophysical, and societal data are being tested at eight diverse geothermal plays and linked to an economic analysis. The technologies are being collected via an open-source toolkit, the FindHeat platform. The platform enables a fast, conceptual model-based exploration workflow that accelerates and de-risks geothermal exploration and appraisal, and facilitates better engagement with various stakeholders (e.g., communities, municipalities, technical experts).*

FindHeat also expands and deploys the Rapid Reservoir Modelling (RRM) tool to generate 3D geological models from the available geological and geophysical data (Jacquemyn et al., 2021). RRM is an innovative tool to create 3D models of complex stratigraphy and structure, with direct applications to rapid prototyping of conceptual models of subsurface reservoirs in situations where data are sparse and geological uncertainty large. RRM was successfully used to create realistic computer models of geological reservoirs for CO_2 storage sites in a matter of hours and assess the impact of the related geological uncertainties on flow behaviour in weeks. This accelerates typical turnaround times for geothermal reservoir modelling and uncertainty assessment from many months to a few weeks. The resulting reservoir models can then be deployed in subsequent numerical simulations to estimate temperature distributions and heat flow rates (Yapparova et al., 2023).

To ensure that a broad range of technical experts and non-technical stakeholders can be reached, tailored training materials are being developed, which can be adapted for the different technical and non-technical audiences to account for their different backgrounds (e.g., geoscientists vs. economists; local communities with different exposure to geothermal energy). This includes developing different, tailored styles of communication (e.g., field trips vs. class-room style training).

Field Sites for Technology Validation

The integrated FindHeat technologies are tested and validated across eight geologically diverse geothermal plays located in Iceland, UK, Spain, Netherlands, France, and Czech Republic, ranging from low- and high-enthalpy geothermal systems to fractured basement reservoirs and superhot geothermal resources (Figure 2). These diverse field sites have also different levels of maturity and hence allow us to demonstrate the economic and technical benefits arising from faster turnaround times for exploration and appraisal of geothermal resources, making better use of legacy data and non-invasive geophysical techniques, and constraining uncertainties with respect to the size of the heat source and the range of possible heat production rates. The specific applications of the technologies are as follows:

- Identify optimal drilling locations and exploitation concepts for high-enthalpy geothermal systems located in volcanic areas based on shape, location, and age of magma storage regions (representing a heat source) and regional hydrogeology (Spain);
- Determine low-risk drilling locations and injection strategies in superhot geothermal resources as an alternative for risky direct production with the benefit of re-charging existing high-enthalpy geothermal fields without negatively impacting production (Iceland);
- Analyse if a new fracture characterisation and modelling workflow would impact the decision-making process how to develop a highly productive low- and medium-enthalpy geothermal system (Iceland);
- Characterise the link between shallow thermal anomalies and hydraulic characteristics of deep-rooted fault networks in low- and medium-enthalpy systems to identify well locations that reliably target the conductive fault segments in fractured basement reservoirs and eliminate the need for stimulation (France and Czech Republic);
- Assess how the 3D architecture (e.g., connectivity, width, tortuosity, and net-to-gross ratio) of fluvial channel sandstones impacts heat flow in low-enthalpy geothermal systems to identify well locations that minimise the risk of early breakthrough of the injected cold water (Netherlands and UK);
- De-risk drilling decisions and optimise exploitation concepts in fractured low- and medium-enthalpy geothermal reservoirs by accounting for uncertainties in fracture network properties when targeting fracture zones with sufficient permeability (France, Czech Republic, and UK);
- Quantify the value-of-information of different geophysical datasets and inversion techniques for improving our understanding of geological concepts and constraining economic uncertainties (all sites);
- Improve community engagement and create better understanding of how geological exploration allows operators to reduce and mitigate technical and economic risks when developing a geothermal resource (all sites).

Economic Analysis and Public Engagement

A probabilistic techno-economic framework (Wang et al., 2023) is used to establish how the different sources of data and deployment of innovative modelling techniques have influenced the understanding of the geothermal system across the eight geothermal plays. This framework enables us to repeatedly and seamlessly update the economic outlook across the eight geothermal plays as geological concepts are refined and geological uncertainties become more constrained when new geophysical data are being collected and interpreted, while also accounting for economic uncertainties such as changes in tax subsidies. This approach allows us to quantify the value-of-information of new datasets for updating and refining geological concepts, and hence the overall economic impact of a conceptual model-based exploration and appraisal strategy for geothermal energy.

FindHeat is executing a multi-step social science approach to improve public communication and understanding of public responses to geothermal exploration and development. This aims to ensure that local communities are included in important decisions by providing a framework where institutions can earn trust, adapt communication to local culture, and reduce irrational psychological biases. A particular advantage herein is that, across the eight geothermal plays, experiences with geothermal energy varies greatly. This allows for considering cultural biases identified through an empirical survey for the plays when analysing and comparing the impact of communication on public perceptions.

Conclusions

The FindHeat project is developing a novel, conceptual model-based geothermal exploration workflow that is being deployed and validated across eight geologically diverse geothermal plays to demonstrate its economic and technical benefits arising from faster turnaround times for exploration and appraisal of geothermal resources. By making better use of legacy data and non-invasive geophysical techniques, uncertainties with respect to the size of the heat source and the range of possible heat production rates are being constrained early in project life, leading to a paradigm shift towards exploiting geothermal resources that have inherently lower risks. This will improve exploration success and economic feasibility, which, together with a new communication strategy that is embedded in social science research, helps to earn the public trust so that geothermal energy can be exploited safely and sustainably.

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