MISSIONE 4 ISTRUZIONE RICERCA

Innovation in GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors

InGEO

NATIONAL RECOVERY AND RESILIENCE PLAN (NRRP) – MISSION 4

COMPONENT 2 INVESTMENT 1.1 – "Fund for the National Research Program and for Projects of National Interest (NRP)"

InGEO Project

1st PERIODIC REPORT

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SUMMARY

SECTION 1
INTRODUCTION TO THE PROJECT

BRIEF SUMMARY OF THE PROJECT

The InGEO project (Innovation in GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors) aims to define a method to quantify the energy realistically producible from deep geothermal energy sources at the regional level to be used for specific technologies, e.g. to generate electricity or for district heating. It will demonstrate an innovative exploration workflow to integrate geophysical data and assess deep underground conditions. This activity consists of the reconstruction of the crustal and subcrustal structures by joint analyses and interpretations of available and acquired geological and geophysical data (e.g., those provided by mechanical and thermal rocks' experiments, seismic and gravity anomalies), taking advantage of the different sensitivity that geophysical methods have on physical rock's parameters (temperature and composition). The results will be the input of the thermal model and contribute to the development of GEOTHERMOS, an open-source and web-based GIS tool, and the calculation of the deep geothermal energy potential for hydrothermal resources and deep heat exchangers.

The outcomes of InGEO are designed for use by investors, regulators, governments, and consumers. They will provide data for energy planning and contribute to developing technologies helpful in reaching regional and national climate neutrality, favouring a shift in the energy mix towards renewables.

OBJECTIVES CONNECTED TO THE PROJECT AND RELATED OUTCOMES

InGEO responds to this need by improving knowledge of geothermal resources and the energy they contain for various uses. The project addresses several technological challenges and aims to:

- develop an effective assessment of deep geothermal resources, taking into account local geological conditions, regime and heat exchange capacity;
- devise operational solutions for energy production and underground heat storage, optimising thermal performance;
- validate the approaches developed in a regional-scale area with a real case study. The reconstruction of crustal and sub-crustal structures and temperature distribution of the buried folds of the Po Valley sector will be the input for the calculation of the geothermal potential, considering different applications (power production, district heating, process heat and combinations) and underground energy exchange technologies (open and closed loops).

The activities target five main Milestones:

1. Set up a database of the interpreted geological and geophysical data for the case study area (Month 6)
2. Set up a database of the petrophysical experiments for the case study area (Month 10)
3. Definition of the deep geothermal exploration and potential assessment workflows (Month 12)
4. Completion of the thermal model of the case study area (Month 18)
5. Implementation of a comprehensive and open-source software tool for assessing the deep geothermal potential (Month 24)

The expected outcomes are:

- A database of petrophysical rocks' parameters.
- A 3D model of the shallow lithospheric structures of the study area based on the integration of the data collected, acquired, analysed, and interpreted in the project.
- A review of deep geothermal potential assessment methods
- An Open-Source software tool, accessible through a web-GIS application, for computing the deep geothermal potential with variable heat extraction modes and production rates
- The thermal performance of deep closed-loop heat exchanger as a function of environmental, design and operating variables.
- Geothermal potential maps of the study area.

InGEO is based on activities organised in three interrelated Workpackages (WP), as shown in Fig. 1.

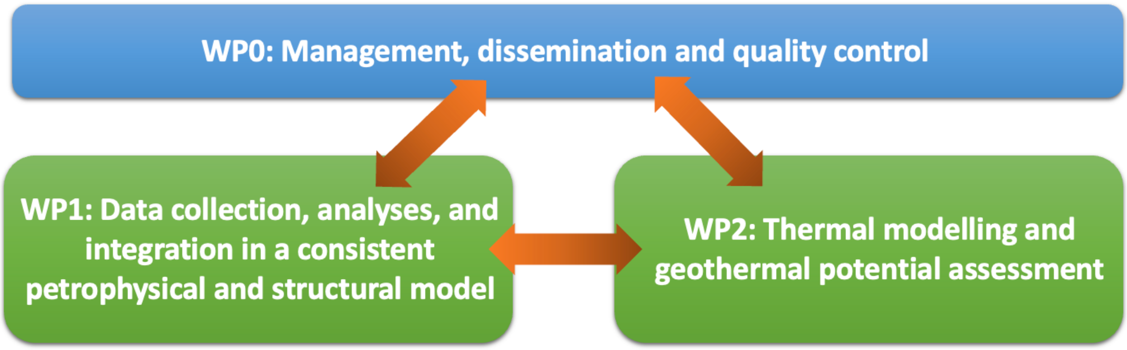

Figure 1: Thematic Work Packages and relations

The core of the technical development of InGEO solutions is carried out in WP1 and WP2. WP1 focuses on integrating geological and geophysical data to implement predictive subcrustal (50 km) models and define a workflow for deep geothermal resource characterization within the first 10 km. WP2 is dedicated to quantifying the deep geothermal resource potential, achieved by defining an assessment workflow implemented with an Open-Source software tool (GEOTHERMOS). The activities are supported by coherent and smooth management and coordination, articulated under WP0.

OPERATIONAL UNITS INVOLVED IN THE IMPLEMENTATION OF THE PROJECT

- Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse (CNR-IGG): it coordinates the project, leads the WP0 (Coordination and Communication) and WP2 (Thermal modelling and Geothermal Potential assessment) and support most tasks of the project.
- Università degli Studi di Trieste, Dipartimento di Matematica e Geoscienze (UNITS): it leads WP1 (Data collection, analyses, and integration in a consistent petrophysical and structural model), which is its main field of activity, and assists the interpretative activities related to the geothermal potential assessment.
- Università degli Studi di Padova, Dipartimento di Geoscienze (UNIPD): it supports all activities with a special focus on petrophysical analyses in WP1 and geothermal potential assessment in WP2.

SECTION 2
PROGRESS OF WP1 ACTIVITIES

TASK A1.1: REVIEW AND INTERPRETATION OF GEOLOGICAL AND GEOPHYSICAL WELL DATA

We focus our study on the Northern Apennine buried structures belonging to the Romagna and Ferrara Folds (RFF), which show a relatively low geothermal gradient within the deep carbonate units (about 14 °C/km) and a significantly higher thermal gradient (about 53 °C/km) in the overlying impermeable cover. According to this evidence, fluid thermal convection occurs in the deep-seated carbonate units of Mesozoic age, composing the local geothermal reservoir.

A geological database has been constructed using published data (e.g., Livani et al., 2023) concerning the tectonic setting of the area and depths of the main seismic horizons (Fig. 1). In addition, we collected geological maps, open-source seismic lines and well log data (Fig. 2). The shallow crust is investigated through a total of 784 exploratory wells (VIDEPI database (https://www.videpi.com/videpi/videpi.asp), with depths ranging from 0.5 up to 7.8 km below ground level. They provide essential information concerning lithostratigraphy, temperatures measured during drilling stops, and geophysical logs, which are used to implement a geological model of the shallow structures.

We also collected, digitised and analysed data from over 200 seismic surveys from the VIDEPI database, 584 deep (>1500 m) boreholes (CNR database) and 160 borehole logs (sonic and lithological logs).

The data are organized using GIS and Kingdom Suite IHS, creating 2D and 3D projects to facilitate geographical organization and initial interpretations.

At the same time, we collected and organized seismic velocity 3D grids of the crust up to the Moho depth (Fig. 3), reviewing the existing literature (Magnoni et al., 2020; Nouibat et al., 2023) and Bouguer gravity anomalies (Zahorec et al., 2021), available from the Alp Array project (Fig. 4).

We observed that most of the study area is characterized by low seismic velocities (Fig.3) in the very shallow crust, probably reflecting the relative high sedimentary thickness in the RFF, which sharply reduces towards the Apennines. The Bouguer anomalies are provided with a resolution of 4 km x 4km and are negative in most of the RFF (Fig. 4), consistently with the low velocities of the shallow crust (Fig. 3).

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FIGURES

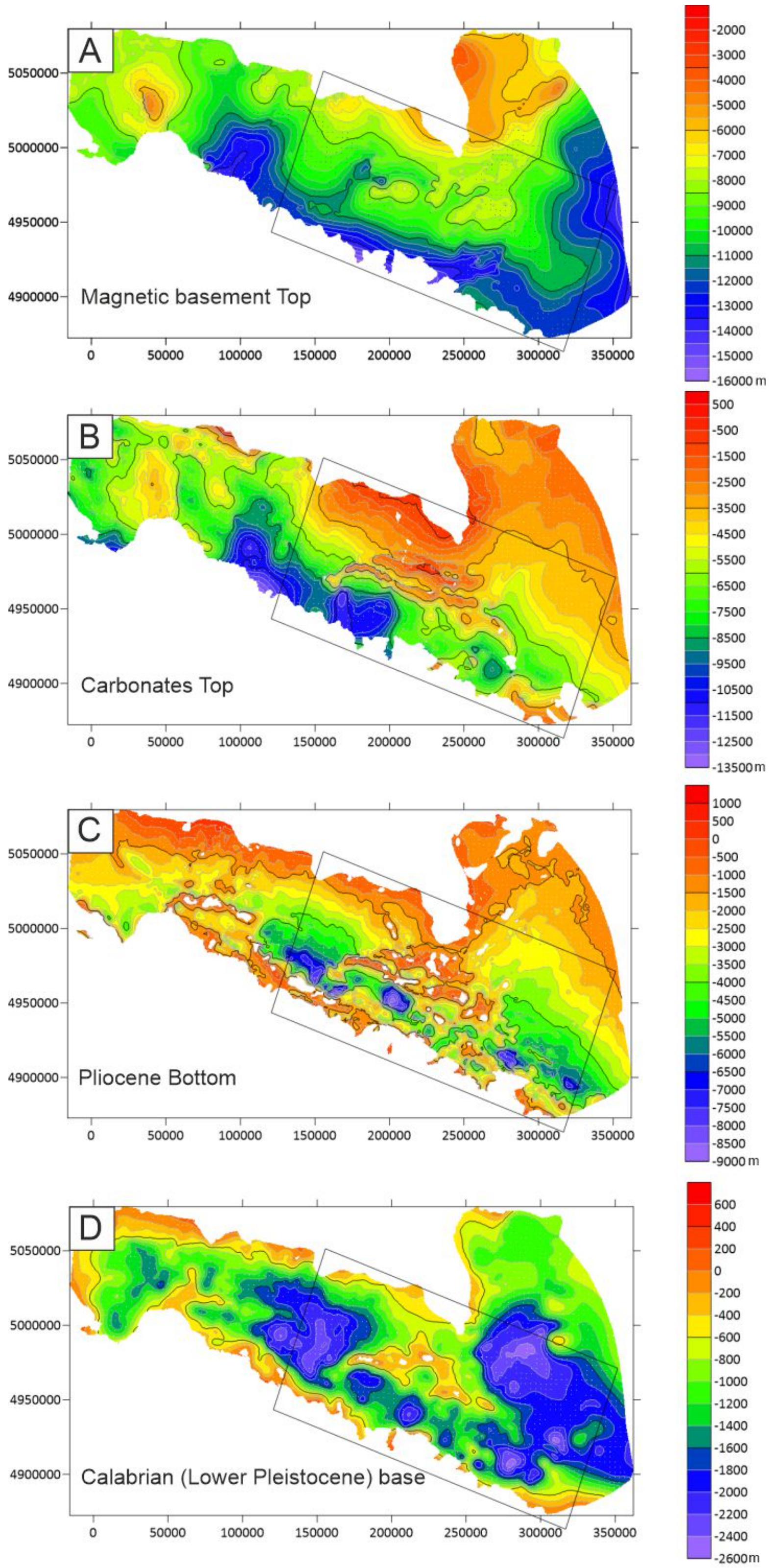

Figure 1. Depth maps of surface: A-Top of Magnetic Basement, B-Top of Carbonate unit, C- Base of Pliocene unit, D- Base of Calabrian (Lower Pleistocene) unit. Black rectangle represents the study area. Modified after Livani et al. (2023).

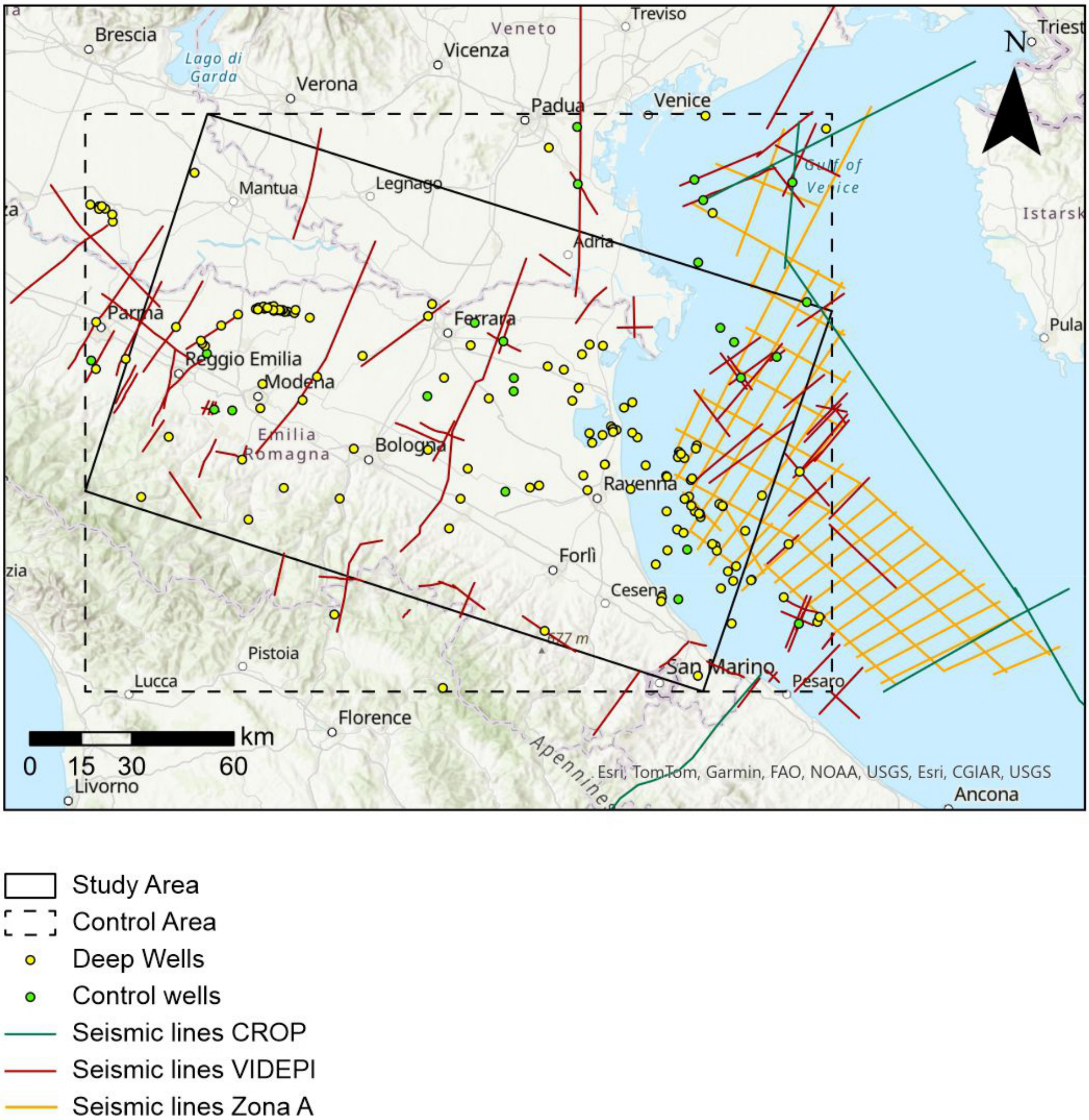

Figure 2. Location of digitalized seismic surveys and well logs.

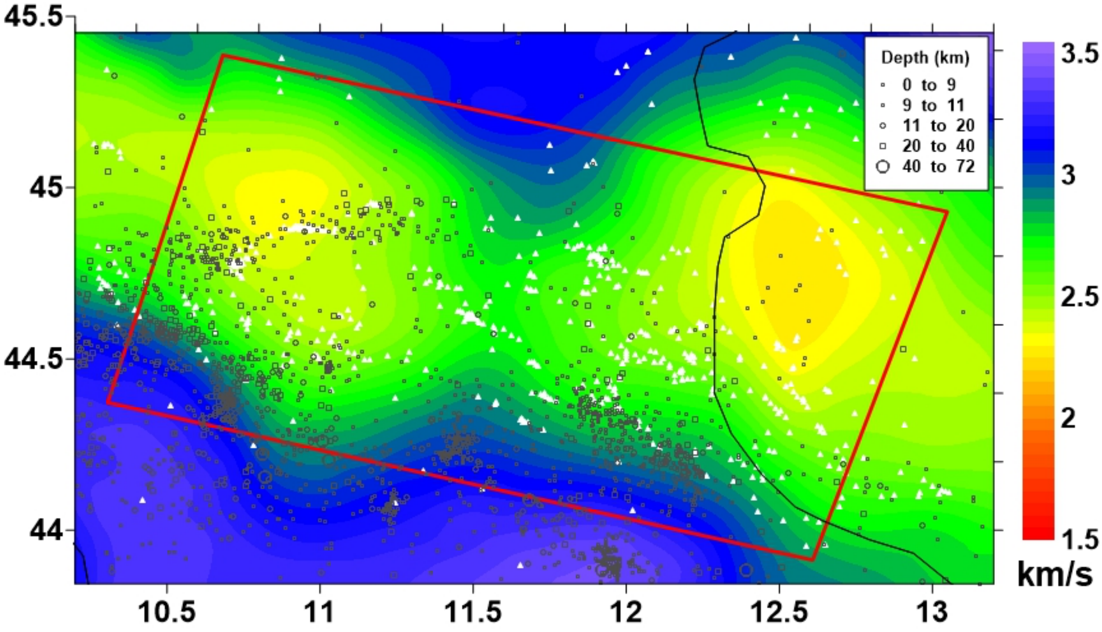

Figure 3. Shear wave velocity at a depth of 2 km (Nouibat et al., 2023). The red rectangle delimits the study area. The black circles and white triangles show the earthquakes and wells location, respectively.

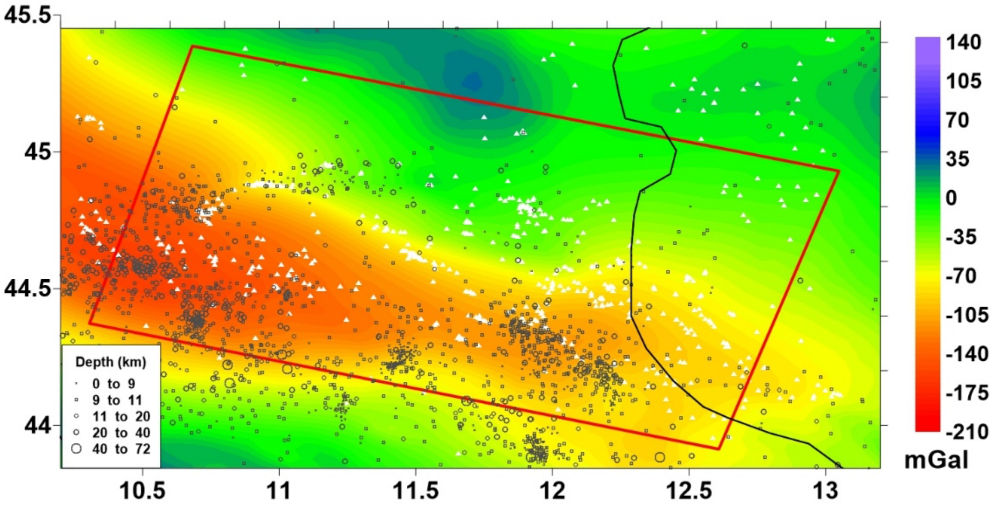

Figure 4. Bouguer gravity anomalies map of the study area from Zahorec et al. (2021). The other features are as in Fig. 3.

SECTION 3
PROGRESS OF WP2 ACTIVITIES

TASK A2.1: REVIEW AND TESTING OF EXISTING CONCEPTS AND TOOLS

Geothermal potential assessment is crucial for developing and investing in geothermal energy projects. Various concepts and tools have been designed to evaluate the potential of geothermal resources, ranging from geological surveys to sophisticated simulation models. This review aims to explore the existing methodologies, their strengths, limitations, and the effectiveness of current tools in accurately assessing geothermal potential.

This activity, foreseen as Task A2.1, has been completed. The literature review included more than fifty articles (review articles, research articles and technical reports) reporting methods for geothermal potential assessment as well as economic assessment. This activity lays the foundations for the next activities:

- *A2.2 - Deep geothermal potential assessment workflow and*
- *A2.3 - Open-Source software tool development.*

3.1 Geothermal power assessment

Overall, there are mainly ten methods to evaluate the geothermal potential, and they can be divided into two main groups based on the type of input data required by the method:

- *A single point or static – methods that do not need production history data*
- *Historical or dynamic – methods that require production history data.*

The methods requiring a single data as input are:

- *Method of surface heat flux*
- *Planar fracture*
- *Magmatic heat budget*
- *Total well flow*
- *Volumetric*
- *Mass-in-Place*
- *Power density*

The methods requiring historical or dynamic data as input are:

- *Decline analysis*
- *Lumped parameter*
- *Numerical reservoir simulation*

The methods are briefly outlined below.

3.1.1 Method of surface heat flux

This method approximates the total theoretical minimum amount of heat that can be withdrawn from a geothermal resource by measuring the heat loss or gain at the ground surface from: 1) Hot springs and geysers, 2) Fumaroles and steaming grounds, 3) Seepages, 4) Mud pools, 5) Thermal grounds. The total amount of heat can be expressed as the sum of the convective and conductive components:

$$q_{tot} = \sum_{i}^{n} q_{si} + q_c$$

where q_{tot} is the total amount of heat, q_{si} is the total thermal energy estimated from the individual surface manifestations and accounts for the convective term, and q_c is the conductive heat flow.

The conductive term can be estimated using the thermal gradient:

$$q_c = Ak\frac{dT}{dz}$$

where A is the surface area of the hot ground [m^2], k is the thermal conductivity of the rock [W/(m °C)], and dT/dz is the thermal gradient [°C/m]. This method can be used for a first rough estimation of the geothermal potential since it is easy to implement. Still, it has been proven to yield unrealistically low estimates of the potential capacity of a geothermal field because the data is prone to error, approximation and subjectivity.

3.1.2 Planar fracture method

In this method, the fluid is heated up by passing through the fractures in the rocks. The theoretical extractable per unit fracture area can be estimated from the end temperature ratio as proposed by Bodvarsson (1974), which is expressed as:

$$r = \frac{T_m - T_{rech}}{T_0 - T_{rech}}$$

where T_m is the Minimum rock temperature [°C], T_0 is the initial rock temperature [°C], and T_{rech} is the Recharge water temperature [°C]. This model can also be applied in case of multiple fractures, but only if there is a minimum distance between them expressed as follows:

$$\frac{d}{2} = 3 * \sqrt{\alpha * t_0}$$

where α is the thermal diffusivity [m2/s] and t0 is the production period [s]. In general, this method is not so useful for the estimation of the geothermal potential since it is focused on a particular geologic setting where the nature of fracture distribution can either be described by a single fracture or by multiple fractures with insignificant interference, but the fracture orientation and distribution are generally unknown.

3.1.3 Magmatic heat budget method

This method is a qualitative assessment of relative potential. It estimates the volumes of silicic magma chambers to predict their emplacement age and to calculate the amount of geothermal energy remaining in the intrusion and adjacent country rock. The conventional calculations of conductive heat loss are applied. However, as the methodology's name implies, it applies only to assessing volcanic and magmatic regions.

3.1.4 Total well flow

This method is a simple approach to summing up the measured output of the well after performing an intensive discharge test. This method demonstrates the ability of the field to deliver fluid but not the total potential capacity, which could be higher if more wells are drilled. At the same time, for pumped wells, the output can be constrained by the casing and/or pump size. So, it gives a reliable minimum estimation of the field potential since the exploration drilling programs do not drill the full field potential upfront of the development, and many developers use a staged approach to field development, which only results in a limited capacity project.

3.1.5 Volumetric method

This method is one of the most used for evaluating the geothermal potential. The power potential can be estimated with the following formula:

$$MW_e = \frac{q \times R_f \times \eta_{conv}}{F \times L}$$

where MW_e is the power potential [MW_e], q is the thermal energy stored in the reservoir [MJ], R_f is the recovery factor [-], η_{conv} is the conversion efficiency [%], L is the plant life [s], and F is the capacity or load factor [%]. The thermal energy q stored in the reservoir can be calculated by dividing the reservoir into n different regions of volume V_i and temperature T_i:

$$q = \sum_{i=1}^{n} \rho_i c_i V_i (T_i - T_f)$$

where ρc is the volumetric heat capacity of a saturated rock [J/(m^3°C)], V_i is the volume of i-th volume, T_i is the initial temperature of i-th volume [°C] and T_f is the cut-off or final abandoned reservoir temperature [°C].

An important factor is the conversion efficiency, which defines how much thermal energy can be converted into electrical energy. The conversion efficiency can be approximatively estimated by adopting calibrated functions, which require as input the temperature or the enthalpy of the reservoir. Alternatively, the thermodynamic cycle of the power plant can be modelled by accounting for all the thermodynamic stages from the turbine to the injection well, including the condenser and the cooling tower.

3.1.6 Mass-in-place method

This method describes a volumetric method which uses the total mass in-place (MIP) instead of stored heat. The mass-in-place method calculates a geothermal resource's total available and recoverable mass by implementing numerical simulation and the volumetric method calculation. The mass recovery factor required for this method differs from the heat recovery factor discussed earlier. This method is prone to underestimating the true potential of the resource.

3.1.7 Power density method

The power density method assumes that power capacity per unit area of the productive resource is a function of reservoir temperature. The power density method requires very few assumptions compared to the other methods for estimating resource potential. However, its applicability and reliability are as good as the data used to generate the plot and the empirical correlation. This method is not applicable to projects in the exploration phase and may not be appropriate when there are only a few wells. Furthermore, the available capacity of geothermal fields changes with time. Overall, the power density method can be useful in providing a rough estimate of resource capacity and may only be applicable as an indicative estimate.

3.1.8 Decline analysis

Decline analysis is a simple method for estimating the resource potential over a short period. It involves fitting known production history data, and the fitted equation is then used to forecast future production capacity. The production data declines with time, and this decline in production is typically assumed to follow harmonic or exponential decline trends. Decline analysis is mainly used as an assessment tool during the production stage. By fitting production history data, an estimate of the likely future output of wells affected by pressure drawdown and operating at a constant wellhead pressure (WHP) and makeup well requirements at different assumed decline conditions can be determined. However, the method is unsuitable for long-term reserves estimation and inferior to a well-calibrated 3D numerical reservoir model.

3.1.9 Lumped parameter

In a simple lumped parameter model, the reservoir is treated as a single box or closed tank. The pressure declines because of fluid withdrawal can be described as a linear function of cumulative production, and the mass and energy equations are often reduced to ordinary differential equations. Similar to decline analysis, the predictive capability of lumped parameter model is still limited and inferior compared to numerical reservoir models.

3.1.10 Numerical reservoir simulation

The numerical reservoir simulation has been proven the most reliable option for geothermal resource assessment. It is a more advanced tool that numerically simulates the physics of fluid flow and heat transfer and the complex nature of reservoir geometry. The three important stages in numerical development are as follows:

- *Conceptual model: it helps to set up the numerical model, understanding the important aspects of the reservoir and the physical process affecting it.*
- *Natural state thermal model: it involves matching the pre-exploitation temperature and pressure profiles and surface manifestation data*
- *Production history matching: with the natural state as the initial condition, production history matching involves simulating field responses to fluid withdrawal and injection*
- *Forecasting: the final model calibrated against pre-exploitation and production history data is used to test various future production scenarios being considered going forward in time.*

3.2 Economic evaluation

The economic evaluation is essential to understand if the project is feasible and will bring a profit To do so, the Levelized Cost of Energy (LCOE) and the Net Present Value

(NPV) must be estimated. The LCOE is the calculation of the life-cycle cost for each unit of energy produced in the lifetime of a project. It allows the comparison of different technologies of unequal life spans, size, costs, risk, return, and capacities.

It can be evaluated through the following formula:

$$LCOE = \frac{CAPEX + \sum_{k=1}^{n} OPEX_k \cdot (1+i)^{-k}}{\sum_{k=1}^{n} E_k \cdot (1+i)^{-k}} \quad \left[\frac{€}{MWh}\right]$$

where the CAPEX is the capital expenditure, i.e. the total amount of the initial investment, the OPEX is the operating and maintenance cost, and E is the production energy. The calculations are yearly based.

The NPV represents the yearly net cash flow of a project. It can be evaluated as:

$$NPV = -CAPEX + \sum_{t=1}^{n} \frac{B_t}{(1+IRR)^t}$$

where B_t is the cash flow at the year t, i.e. the difference between the revenues of the year and the operating and maintenance cost, IRR is the internal rate of return, which is the value that makes the discounted cash flow equal to the investment cost.

3.2.1 Risk-adjusted discount LCOE

The Risk-adjusted Discounted Levelized Cost of Energy (LCOE) is a metric used in the energy sector to assess the cost-effectiveness of different energy projects while incorporating risk factors. Traditional LCOE calculates the per-unit cost of building and operating a generating plant over its assumed financial life and output. However, it doesn't account for various risks, such as market volatility, regulatory changes, and project-specific uncertainties. Risk-adjusted LCOE modifies this approach by including a discount rate that reflects these risks. This rate is higher for projects with more significant uncertainty, effectively increasing the cost estimates for riskier ventures. This adjustment provides a more realistic and comprehensive cost assessment, enabling investors and policymakers to make better-informed decisions.

The key advantage of using Risk-adjusted LCOE is that it offers a clearer picture of the actual economic viability of energy projects, promoting investments in projects with sustainable risk profiles. However, it also introduces complexity and subjectivity in selecting the appropriate discount rates, which vary widely based on risk perception and market conditions.

Overall, Risk-adjusted LCOE is a valuable tool for enhancing the financial evaluation of energy projects, ensuring a balanced consideration of cost and risk. The traditional formula to evaluate the LCOE using a risk-adjusted discounting approach is:

$$LCOE_{RAD} = \frac{\left(\sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1 + R_{RAD})^t}\right)}{\left(\sum_{t=1}^{n} \frac{E_t}{(1 + R_{RAD})^t}\right)}$$

where C_t is the capital and decommissioning cost, O_t is the fixed operating cost, V_t is the variable operating cost, E_t is the energy generated in period t, and R_{RAD} is the risk-adjusted discount rate. The R_{RAD} is needed to derive the risk-adjusted LCOE, which is traditionally set as the weighted average cost of capital (WACC) from comparable projects or industry averages.

Pros:

- Enhanced Accuracy: Provides a more accurate reflection of project costs by incorporating risk factors, leading to better-informed investment decisions.
- Comprehensive Risk Evaluation: Allows for a detailed assessment of potential financial risks and uncertainties, which can improve risk management strategies.
- Improved Comparability: Facilitates comparison of projects with different risk profiles on a more even footing.

Cons:

- Complexity: The methodology can be more complex to implement and requires detailed risk assessments, which might not be feasible for all stakeholders.
- Subjectivity: The adjustment of the discount rate involves subjective judgments about risk, which can vary between analysts and affect consistency.

3.3 Conclusions

This review highlights that no single tool or concept can comprehensively assess geothermal potential. Instead, combining geological, geophysical, geochemical, and numerical modelling approaches is often necessary. The effectiveness of geothermal resource assessment methods heavily depends on the type and quality of available data. Different methodologies are suitable for varying levels of data availability, ranging from minimal data to extensive datasets.

SECTION 4
MANAGEMENT, COMMUNICATION AND DISSEMINATION

MANAGEMENT

Management activities essentially covered the preparation of technical reports and administrative documents, the organisation of project meetings, the recruitment of young researchers. Two on-site meetings, in December 2023 and May 2024, were organised at the University of Padova. On-line meetings were organised in occasion of reporting periods or for scientific discussions.

COMMUNICATION

The dissemination activity started with preparing an **InGEO poster,** which briefly describes InGEO's objectives and foreseen results. The poster was published in the institutional websites of the InGEO Research Units:

For CNR at *https://www.igg.cnr.it/ricerche/progetti-finanziati/ingeo*
For UNITS at *https://www.units.it/news/units-nel-progetto-ingeo-finanziato-dal-pnrr-lo-sviluppo-della-geotermia-italia*

For UNIPD at *https://www.geoscienze.unipd.it/progetto-prin-2022-pnrr-innovazione-nella-valutazione-del-potenziale-delle-risorse-e-riserve*

The poster, released in Italian and English in December 2023, was updated in January 2024 after the Ministry released detailed instructions for using the logo.

The project website (https://www.ingeo.cnr.it) was launched in January 2024. The website is bi-lingual, in Italian and English, and describes the project objectives, expected results, and the Project Team. A page containing the produced products, such as abstracts, presentations and posters at scientific events, the project reports, and the documents and tools released in InGEO has been added in March 2024.

DISSEMINATION

- The main project concepts have been described and presented as an oral presentation at the Annual Conference of GNGTS (National Group for Solid Earth Geophysics), which took place in Ferrara from February 13 to 16, 2024. The abstract and the presentation are titled "InGEO: Innovation in geothermal resources and reserves potential assessment".
- An abstract and a poster have been prepared for the EGU (European Geosciences Union) General Assembly and Conference, which took place in Vienna, Austria, from 14 to 19 April 2024. They were titled "InGEO: GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors" and described the project, its objectives, the study area, and the workflow for geophysical data integration.

The description of the geophysical database and some preliminary data collected were described in two abstracts for the SGI (Società Geologica Italiana) Conference, to be held in Bari in September 2024. A description of the challenges for geothermal potential assessment, a review of methods, and a first draft of the workflow have been presented in a seminar titled "Numerical modeling of hydrothermal systems for geothermal potential assessment" at the Politecnico di Torino (date 28/05/2024).

All abstracts, presentations and posters are available the InGEO website (https://www.ingeo.cnr.it/prodotti/).