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From Geothermal Plays to Potential assessment: a Systematic Geothermal Evaluation of Italy

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INTRODUCTION

Italy is a geothermal country indeed, producing almost 6 TWh of electricity per year and about 2700 GWh of thermal energy for thermal uses. The use of geothermal energy in Italy can potentially grow a lot in the next years because the territory is extremely endowed to host geothermal resources in its underground. Such potential is not completely exploited mainly as the lack of knowledge of the underground and data useful to assess the geothermal resources are not existing or available. The assessment of geothermal resources and reserve estimation are crucial in the preliminary stages of a development project to support decision-making, financing, development and operation (Ciriaco et al., 2020).

In Italy, the last national wide assessment of Italian geothermal resource was conducted in 1990s as part of the National Inventory of the Geothermal Resources project. This classification, carried out by a joint venture involving ENEL, AGIP, CNR and ENEA, was based on underground temperature distribution combined with a qualitative hydrogeologic evaluation of geological formations (Cataldi et al. 1995). Afterward, other geothermal resource assessments were performed, often at the local scale, using numerical and semi-automated methodologies (Montanari et al. 2017; Trumpy et al. 2015 and 2016).

In this case study, to accelerate geothermal development in Italy and to aid early assessment of potential resources, we applied a multi-level approach to rank the geothermal resources in the Italian territory. Firstly, the Italian territory was classified based on the geological setting and the main process of heat transfer following the protocol proposed by Moeck in the 2014 and the updates (Moeck and Beardsmore 2014, Moeck et al. 2015 and Moeck at al. 2019) (level 1). Secondly, plays constrained by borehole data were selected, thus the geothermal potential was estimated as the total amount of heat available in the reservoir, known as Heat in Place (HIP) and/or theoretical thermal energy storage in medium/high-temperature aquifers (MT/HT-ATES) (level 2). All the resulting data were organised into GIS database, enabling the rapid identification and visualization of the most promising geothermal areas across Italy beside the descriptive attributes.

1 LEVEL 1: GEOTHERMAL PLAY IDENTIFICATION

Geothermal play type identification in Italy was guided by the plate tectonic setting, the geological characteristics of potential geothermal reservoirs, and the corresponding heat transfer mechanisms, as outlined in the literature (Moeck, 2014; Moeck et al., 2015, 2019).

Existing information gathered from literature such as geological maps (Della Vedova et al., 2001; Carminati et al., 2004; Bosellini et al., 2017), heat flow maps (Cataldi et al., 1995; Della Vedova et al., 2001), the thermal spa localizations, the geothermal uses map and the boundaries of active geothermal leases in Tuscany were integrated in the QGIS environment producing a comprehensive vectorial map of the geothermal play types in Italy. In particular, the drawing procedure included the following criteria: a) the emerged parts of volcanic islands such as Ischia, Pantelleria, and the Aeolian Arch were considered as play area; b) in municipalities such as Milan, Grado, and Ferrara, where the use of the geothermal resource is known, the play area coincides with the administrative municipal boundaries that use the geothermal resources; c) in chain areas and for adjacent foreland and foredeep areas, the tectonic scheme reported in Carminati et al. 2004, 2012 was followed; d) in areas such as Larderello and Amiata, where geothermal fields are known, heat flow lines from Della Vedova et al. (2001) and existing geothermal leases areas were considered.

1.1 Geothermal play in Italy

Italian convection-dominated geothermal systems are classified into the "Volcanic Field" type (CV1), found in active volcanic areas such as Etna, Vesuvius, the Phlegraean Fields, and volcanic islands like the Aeolian Islands, Pantelleria, and Ischia, as well as submarine volcanoes in the southern Tyrrhenian Sea. These systems are further divided into extrusive (CV1a) and intrusive (CV1b) magmatism (Peccerillo 2017). The "Pluton" type (CV2) is represented by geothermal systems at Larderello and Mount Amiata, where the heat source is linked to magmatic intrusions. Larderello and Mount Amiata are classified as CV2b due to the absence of recent volcanic activity (Santilano et al. 2015). Additionally, two extensional fault-controlled systems (CV3) are found in regions with active tectonics: one stretching from Tuscany to Campania, and another in the Campidano Graben in Sardinia.

In Italy, conduction-dominated geothermal plays include Orogenic Belt types (CD2b), located within the Alpine and Apennine belts and their adjacent foreland and foredeep areas (e.g., the Apulian and Hyblaean forelands, the Po River Basin, and the Venetian Plain), classified as CD2a (Vai and Martini 2001). Most of the Calabrian Arc and Sardinia belong to the Basement (crystalline rock) play type (CD3) (Aldega et al. 2011; Paternoster et al. 2017; Donato et al. 2021). The Intracratonic play type (CD1) has not been identified in Italy.

2 LEVEL 2: EXPLOITED AND POTENTIAL RESERVOIRS IN ITALY

The Geothermal Play Type map (Figure 1) provided a basis for identifying areas in Italy where the geothermal potential for deep exploitation and thermal energy storage in medium- to high-temperature aquifers (MT/HT-ATES was assessed. We selected geothermal plays from the Geothermal Play Type map based on a thorough literature review and on available borehole data. The selection focused also on geothermal plays with well-documented potential and currently exploited reservoirs. The selected geothermal plays were organized in ESRI SHP files to collect specific attributes for exploited and potential reservoirs. The new SHP file was built taking into consideration underground temperature at 1 km depth below the ground level and the boundaries of the existing geothermal leases which acted approximately as reservoir extent.

2.1 Geothermal assessment

At the regional scale, where data and parameter constraints on geothermal resources are typically limited, the volumetric method is widely used to estimate the potential heat production capacity of geothermal prospects (Muffler and Cataldi 1978, Ciriaco et al. 2020).

The geothermal potential was calculated using the "1D HIP/HSP Calculator", a Python-based tool developed by the Institut Cartogràfic i Geològic de Catalunya (ICGC) as part of the GSEU project. This software, adapted from the open-source GeothermoTool (Hu et al., 2022), performs one-dimensional stochastic simulations of HIP (Muffler & Cataldi, 1978) and theoretical HSP (Frick et al., 2022) using five probability distribution functions: constant, uniform, triangular, normal, and Laplace for the input parameters.

Heat in Place (HIP) represents the total thermal energy stored in a reservoir, including both the rock matrix and pore fluids, and is quantified by the following expression:

$$\boldsymbol{HIP = V \cdot [\emptyset \cdot \rho_F \cdot C_F + (1 - \emptyset) \cdot \rho_R \cdot C_R] \cdot (Tr - Ti)}$$

where V —reservoir's volume m^3, calculated as A (area) × b (thickness), ϕ —porosity dimensionless, ρ —density kg/m^3; subscripts R = rock, F = fluid, C —specific heat capacity kJ/(kg·°C); subscripts R = rock, F = fluid, Tr — reservoir temperature °C, Ti —reference temperature °C (fixed at 30°C to compare the different potential of all reservoir),

The theoretical Heat Storage Potential (HSP) evaluate the storage capacity of a reservoir and incorporate a recovery factor and a packing correction factor. The effective storage volume is conservatively assumed to be half of the total reservoir volume. A recovery factor of ~70% is applied to represent annual charge-discharge efficiency, while a packing correction factor of ~80% accounts for conservative square-grid packing. The Heat Storage Potential packing correction factor, recovery factor, and "half volume" (or effective volume/porosity) are parameters introduced to reconcile theoretical maximum estimates with realistic and sustainable geothermal energy extraction. These factors are essential to account for geological heterogeneities and thermodynamic constraints.

$$\boldsymbol{HSP = (0.5 \cdot V) \cdot [\emptyset \cdot \rho_F \cdot C_F + (1 - \emptyset) \cdot \rho_R \cdot C_R] \cdot (Ti - Tr) \cdot Fr \cdot Fp}$$

where V —reservoir's volume m^3, calculated as A (area) × b (thickness), ϕ —porosity dimensionless, ρ —density kg/m^3; subscripts R = rock, F = fluid, C —specific heat capacity kJ/(kg·°C); subscripts R = rock, F = fluid, Tr —

reservoir temperature °C, Ti —reference or target temperature °C (fixed at 60°C. and 90°C), Fr is the recovery factor dimensionless, fixed at 0.7, Fp is the packing correction factor dimensionless, fixed at 0.8. The reference or target temperature for the theoretical Heat Storage Potential assessment will be set at 60 °C (for MT ATES) and or 90 °C (for HT ATES).

The availability of borehole data from the National Geothermal Database (Trumpy and Manzella, 2017) enabled an accurate analysis of potential and in exploitation reservoirs as well as providing data for the geothermal potential computation. Borehole lithostratigraphic and temperature data allowed the definition of the geothermal reservoir thickness. The knowledge of the principal reservoir lithologies aided to collect the petrophysical parameters from literature data (i.e., density, thermal conductivity, porosity) which were used as input data for the 1D HIP/HSP code. The reservoir thickness, representative temperature, and petrophysical parameters constitute the main sources of uncertainty, collectively controlling the overall uncertainty of the computed results. Consistent with this, the uncertainties of HIP and HSP are expressed through probability distribution functions. In this study, representative temperature thresholds for medium- and high-temperature storage were adopted to estimate the HSP potential of the reservoirs. Specifically, the HSP potential was considered only for reservoirs with temperatures between 30-60 °C (for MT ATES) and 60-90 °C (for HT ATES), respectively; beyond these limits, heat storage is regarded as not technically feasible (Kallesøe, A.J. & Vangkilde-Pedersen, T. 2019).

3 RESULTS

The Italian peninsula was classified in 27 geothermal plays covering the whole territory. In Figure 1, the following play types were recognized: i) CV1a: Latium Area, Vesuvius, Phlegrean Fields, Ischia, Aeolian Arch, Etna, Pantelleria, Marsili and Vavilov; ii) CV2b: Larderello (Table 3,1) and Mt. Amiata; iii) CV3: Campidano Graben; iv) CD2a: Po basin/Venetian plain , Milan, Ferrara, Grado, Euganean Hills and Apulia and Iblean foreland; v) CD2b: Alps, Apennines, SW Sicily, Guardia Lombardi, Pre-Apennines Tosco-Laziale belt; vi) CD3: Calabrian Arc, Sardinia, North Sardinia and Sicily.

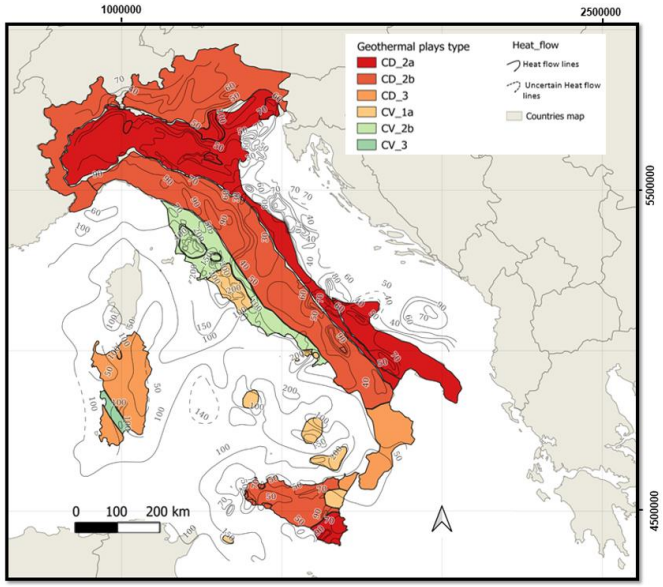


Figure 1. Map of Italian geothermal plays: according to the legend the different geothermal play types were drafted beside the surface heat flow lines (from Della Vedova et al. 2001)

15 selected geothermal play were recognized and organized in a vectorial GIS layer (Figure 2) for which geothermal potential as HIP and HSP were computed, table 1.

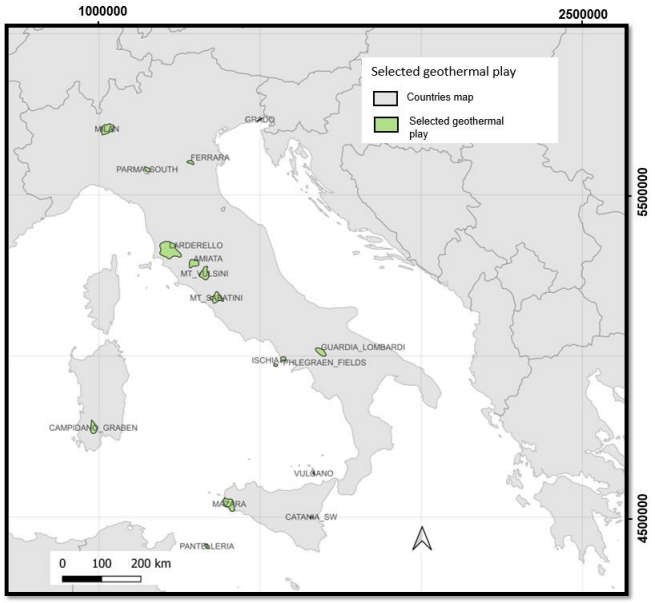


Figure 2. Map of the selected geothermal play types where geothermal potential was assessed.

Table 1 HIP and HSP computation results of the selected geothermal play types

N	Selected play type	HIP(PJ) (P50)	HSP(PJ) Tr=60℃ MT-ATES (P50)	HSP(PJ) Tr=90℃ HT-ATES (P50)
1	Larderello	838000		
	Larderello [shallow]	125000	N.A.	N.A.
	Larderello [deep]	713000	N.A.	N.A.
2	Amiata	263600		
	Amiata [shallow]	18600	N.A.	N.A.
	Amiata [deep]	245000	N.A.	N.A.
3	M. Sabatini	149000	N.A.	N.A.
4	M. Vulsini	50500	N.A.	N.A.
5	Phlegrean fields	102000	N.A.	N.A.
6	Ischia	8590	N.A.	N.A.
7	Vulcano Island	467	N.A.	N.A.
8	Catania SW	173	64.00	177.00
9	Mazzara	16200	N.A.	2010.00
10	Pantelleria	500	9.00	156.00
11	Guardia Lombardi	23300	N.A.	N.A.
12	Ferrara	11900	N.A.	N.A.
13	Grado	311	87.00	261.00
14	Milano	3680	776.00	2480.00

15	Parma south	7490	320.00	1060.00

4 DISCUSSIONS AND CONCLUSIONS

This paper presents a map of Italian geothermal play types (27 areas) and potential reservoirs for deep geothermal exploitation or thermal storage (15 areas). The proposed classification system provided a standardized method for categorizing geothermal resources, aiding exploration and project development. While not exhaustive, the map serves as a foundation for identifying areas that require further study and exploration. Some regions are well-documented with available data, while others, though less accurate, may still hold untapped geothermal potential. The study proposes the geothermal conditions of 15 representative plays in Italy, quantifying exploitable resources and heat storage potential through HIP and HSP calculations. The results demonstrate significant potential for geothermal development, supporting clean energy initiatives and greenhouse gas reduction.

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