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Advancing Geothermal Energy in Small Volcanic Islands: An Overview on the Aeolian Islands (Italy) and IRGIE Project

Monia Procesi[1], Barbara Cantucci[1], Massimo Chiappini[1], Giovannella Pecoraino[1], Maria Giulia Di Giuseppe[1], Fabio Di Felice[1], Gabriele Tarabusi[1], Jacopo Cabassi[1,2], Franco Tassi[1,2,3], Ambrogio Alfieri[4], Claudio Alimonti[5,6], Mohaman Dan Azimi[7], Rina Bartalini[6], Lorenzo Brusca[1], Sergio Calabres[1,8], Francesco Capecchiacci[1,2,3], Corrado Castellano[1], Daniele Cinti[1], Massimo Crescimbene[1], Gilda Currenti[1], Claudio De Paola[1], Francesca Di Laura[1], Federico Florindo[1], Antonio Galgaro[7], Salvatore Inguaggiato[1], Roberto Isaia[1], Federica La Longa[1], Matteo Lelli[1,2], Manfredi Longo[1], Gianluca Lo Re[4], Rosalba Napoli[1], Roberta Maffucci[1], Valeria Misiti[1], Giordano Montegrossi[2], Barbara Nisi[2], Anna Pellizzone[9], Monica Piochi[1], Antonio Troiano[1], Orlando Vaselli[1,2,3], Nunzia Voltattorni[1], Fabio Vita[1], Francesca Zorzi[3]

[1] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy
[2] Consiglio Nazionale delle Ricerche (CNR), Istituto di Geoscienze e Georisorse (IGG), Italy
[3] Università degli Studi di Firenze, Dipartimento di Scienze della Terra, Italy
[4] Regione Siciliana, Ufficio Regionale per gli Idrocarburi e la Geotermia, Servizio Geologico e Geofisico, (Italy)
[5] Università La Sapienza, Dipartimento di Ingegneria Chimica, Materiali, Ambiente, Roma Italy
[6] Unione Geotermica Italiana (UGI), Pisa, Italy
[7] Università degli Studi di Padova, Dipartimento di Geoscienze, Padova, Italy
[8] Università degli Studi di Palermo, Scienze della Terra e del Mare, Italy
[9] Fondazione Giannino Bassetti, Milano, Italy

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ABSTRACT

Small islands frequently face significant challenges in power provision due to their isolation and insufficient infrastructure. To meet energy demands quickly, unsustainable solutions are often employed. Geothermal energy offers a promising and sustainable alternative, particularly as part of a diversified renewable energy mix. This is especially relevant for volcanic islands such as the Aeolian Archipelago (Italy), i.e. an active volcanic arc consisting of seven islands and several seamounts in the southern Tyrrhenian Sea. Volcanic activity above sea level has occurred entirely during the Quaternary period, likely beginning around 400 ka and continuing to the present. The Aeolian Islands cover a total area of approximately 115 km² and include three main islands—Vulcano, Lipari, and Salina—alongside four smaller islands. The resident population of about 15,000 swells to around 300,000 during the tourist season, causing sharp peaks in energy demand, particularly in summer. Currently, as the islands are not connected to the mainland electrical grid, power is primarily generated by small diesel plants, which have substantial environmental, economic, and logistical drawbacks. As a result, the archipelago's sustainability index remains below 30%, underlining the urgent need to harness renewable energy sources.

The four-year Italian project IRGIE (*Inventory of Geothermal Resources of the Aeolian Islands*, 2023–2026) aims to achieve energy independence for the islands from fossil fuels by exploiting geothermal energy. IRGIE is led by *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) and funded by Regione Siciliana – Department of Energy. The project involves universities, research institutions, and industry professionals specialized in geothermal exploration and exploitation. The project's main objectives are to: i) identify and characterize low-, medium-, and high-enthalpy geothermal systems across the archipelago; ii) assess both the theoretical and effective geothermal potential; iii) provide recommendations for appropriate technologies, integrating numerically modelled geothermal resources with the most suitable exploitation methods, while considering local energy demand and the environmental integrity. A further key component of IRGIE is to evaluate public perception of geothermal energy among island residents and stakeholders, and to promote educational and outreach activities aimed at increasing knowledge and awareness of geothermal energy and its benefits among both adults and young people. Preliminary results from geochemical and geophysical surveys offer valuable insights into geothermal potential and underlying hydrothermal-magmatic dynamics. These results lay the groundwork for future exploration and sustainable development strategies.

1. INTRODUCTION

The energy transition on small islands faces a range of geographic, infrastructural, and social barriers. The Aeolian Islands in southern Italy, due to their active volcanic processes and presence of several geothermal manifestations, represent a natural laboratory for studying geothermal systems. Moreover, they offer a compelling case where geothermal energy could now play a strategic role in transforming the local energy landscape. Many islands worldwide are of volcanic origin; in this context, the use of geothermal energy for power and heat could represent a powerful and sustainable solution within a broader transition toward fully renewable energy systems, particularly from an energy mix perspective.

Several islands and island states—such as Japan, New Zealand, Indonesia, and the Philippines—already utilize geothermal energy, though primarily on larger islands with power systems comparable to those of continental regions. Despite its high efficiency and minimal land use, geothermal energy remains underrepresented for island energy transition strategies. A review of 100% renewable energy scenarios shows that only a limited number of studies—mainly focusing on islands such as Terceira, La Réunion, and St. Vincent—consider geothermal energy alongside other renewables, highlighting a notable gap in integrated planning (Procesi, 2025). Considering the very low sustainability index of the Aeolian Archipelago—less than 30%—there is a pressing need to develop new energy solutions (Battistelli et al., 2024), particularly through the integration of geothermal energy with other renewable sources such as solar and wind.

2. GEOTHERMAL CHARACTERIZATION OF AEOLIAN ISLANDS

2.1 Geological setting and past geothermal exploration

The Aeolian Islands constitute a volcanic archipelago associated with the Africa–Eurasia convergence zone, consisting of seven main islands with a total surface area of approximately 115 km². Vulcano, Lipari, and Salina are the largest islands, while Stromboli, Panarea, Filicudi, and Alicudi are relatively small, ranging in size from 3 to 12 km² (Fig. 1a-b). These islands have developed around and within the Marsili Basin, a rapidly expanding back-arc basin (Nicolosi et al., 2006) underlain by basaltic rocks and characterized by a thin lithosphere and crust (Trua et al., 2004). The Aeolian arc is a volcanic chain characterized by composite structures formed through the accumulation of multiple eruptive centers and repeated volcanic and tectonic events, including sector and central collapses. The exposed rocks are younger than approximately 270 ka (Leocat, 2011). Currently, Vulcano and Stromboli are active, while the other islands have not shown historical eruptions although they are currently characterized by hydrothermal activity, except of Alicudi. The arc is intersected by a complex system of faults (Ventura, 2013). Among these, the NW–SE-trending Tindari–Letojanni Fault (TLF) is the most prominent tectonic structure, extending from the Salina–Lipari–Vulcano alignment to the Malta Escarpment. Traditionally, the Aeolian arc has been divided into three sectors based on volcanological and structural characteristics: the western arc (Alicudi and Filicudi), the central arc (Vulcano and Lipari), and the eastern arc (Panarea and Stromboli). The central islands lie along the TLF, where a strike-slip tectonic regime prevails, while Salina is positioned at the intersection of E–W-trending faults of the western arc and the TLF. Panarea and Stromboli lie along SW–NE-trending extensional faults.

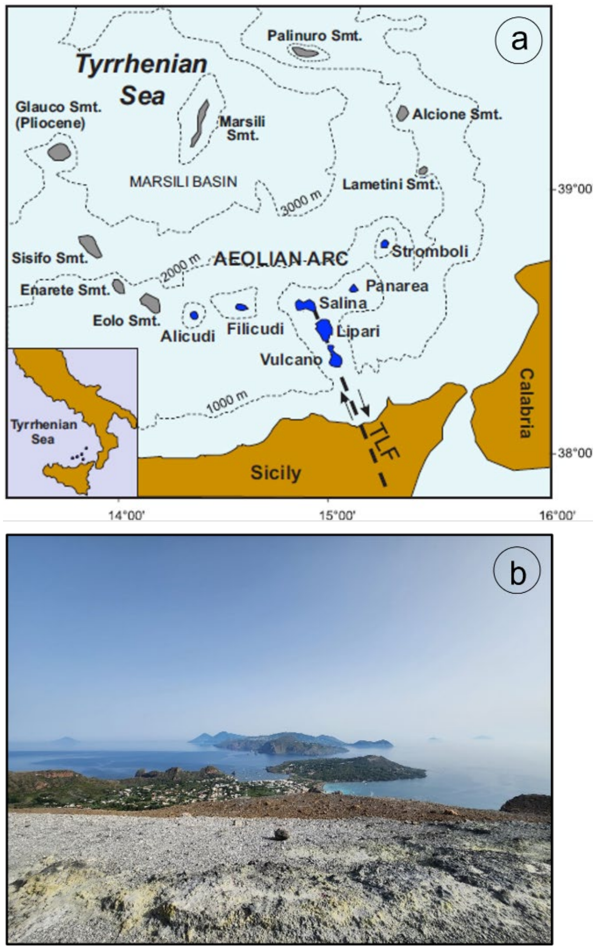

Figure 1: a) Location map of Aeolian Islands and seamounts (from Peccerillo et al., 2013); b) Panoramic view from Vulcano island: in the foreground, Lipari and Salina; to the right, Panarea and Stromboli; to the left, Filicudi (© G. De Astis).

Geothermal exploration in the Aeolian Islands began in the 1950s, with initial investigations focused on Vulcano. During this early phase, two wells were drilled to depths of approximately 235 meters. Temperatures approaching 200 °C were recorded at around 200 m depth. However, the results also revealed a discontinuous and highly variable flow rate (ranging from 0.35 to 6.6 t/h) and fluctuating dry-steam content (between 90% and 30%). During ‘80s, two more wells were drilled, at depth between 1,700 and 2,000 meters. High temperatures were recorded but associated to very low permeability. A surface geothermal exploration was also conducted in Lipari, beginning with geochemical survey, which involved the collection of 150 water samples and 8 free gas samples. After these results, the geothermal exploration throughout the Aeolian Archipelago, was abandoned. At that time, the geothermal industry focused exploration of 'dry steam' fields with high efficiency. Systems dominant in the liquid phase or poor in fluids were discarded due to limited industrial interest. Geothermal exploration was in practice demarcated to the most spectacular manifestations to the exclusion of potential systems that could worthily respond to a less conventional use by the standards of the time. These choices, unfortunately, contributed to the current energy options, considered unsustainable, but dictated by the need to meet local energy demand and cope with the difficulties of not being connected to the national electricity grid.

2.2 Current geothermal exploration in the framework of IRGIE project

Following the earlier phase of geothermal exploration, which was abandoned largely due to the focus on high-efficiency dry-steam systems, a renewed interest in the geothermal potential of the Aeolian Islands has emerged through the IRGIE project. This initiative aims to investigate the geothermal characteristics of the entire archipelago using a multidisciplinary approach. Unlike past efforts, the project emphasizes a comprehensive geochemical characterization of surface manifestations and existing wells to better understand water–gas–rock interaction processes and the physicochemical nature of geothermal fluids. Through systematic sampling and analysis of thermal springs, fumaroles, and well discharges, the project seeks to estimate subsurface reservoir temperatures using geothermometers and to define the chemical signatures of the geothermal fluids. In parallel, geophysical surveys are being integrated to support the construction of conceptual circulation models. These models are crucial for visualizing the fluid pathways, understanding the structural controls on fluid movement, and estimating the potential volume of geothermal reservoirs. The ultimate goal is to assess the theoretical geothermal potential by constructing a volumetric model of the geothermal system across the Aeolian Islands. Additionally, the project seeks to identify the most suitable applications of these resources and, at selected sites, to estimate their technical geothermal potential.

2.2.1 Geochemical survey

Geothermal systems typically consist of hot rock volumes with variable porosity, intersected by faults and fractures that facilitate the circulation of hydrothermal fluids. These fluids often originate from deep sources and interact with meteoric recharge, accumulating in permeable zones that can act as geothermal reservoirs. To investigate on the origin of the fluids occurred on the Aeolian Islands, and on the related water-gas-rock interaction processes, several geochemical campaigns were carried out on the archipelago. A total of 66 waters from thermal wells and few springs were collected from the islands of Lipari, Salina, Vulcano, Panarea and Stromboli (Fig. 2).

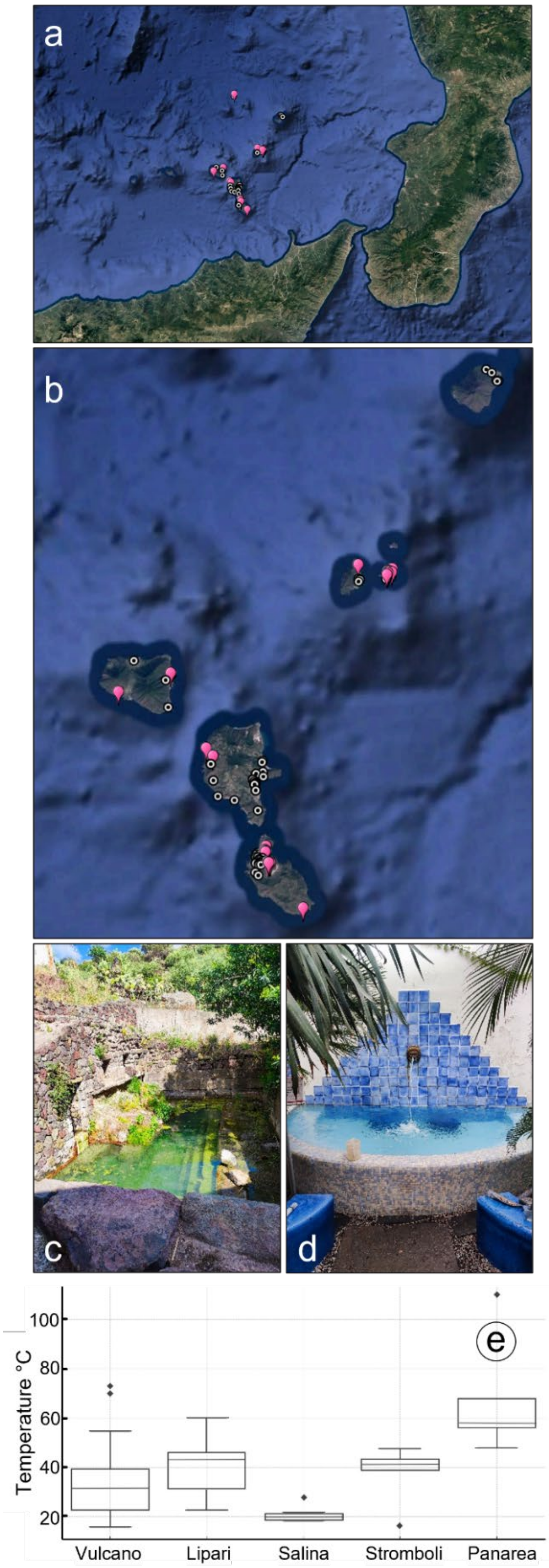

Figura 2: a) Location of the Aeolian archipelago; b) Detailed view of the study areas, white dots and pink pins indicate water and gas sampling points, respectively; c) Thermal spring at Terme di S. Calogero, Lipari; d) Thermal well in Lipari; e) Box plot showing temperature distributions of the sampled thermal springs and wells.

Temperature (T), pH, electrical conductivity (EC), redox potential (ORP) as well as HCO_3^- were determined in the field with a multiparametric probe and acidimetric titration, respectively. Main anions and cations, trace elements, stable water isotopes, dissolved gases, $\delta^{13}C$-CO_2 and $\delta^{13}C$-TDIC values, and isotopes of noble gases were analysed in the laboratory. Twenty-eight gas samples were collected from fumaroles and submarine gaseous emissions, mainly on Vulcano and Panarea islands, focusing on crater fumaroles and submarine gas vents, respectively. Notably, gaseous manifestations associated with bubbling pools in the sea were also identified and sampled for the first time on Lipari and Salina. The main gas composition and the isotopic signatures of $\delta^{13}C$-CO_2 and noble gases were determined. Preliminary results indicate that geothermal reservoirs on Vulcano have estimated temperatures ranging from 180°C to 240°C, with strong evidence of water–rock interaction processes. At Stromboli, groundwater exhibits mixed marine and volcanic contributions. Panarea hosts a significant geothermal system extending from the main island to offshore submarine fluid discharges, characterized by temperatures up to 110°C and reservoir temperatures likely exceeding 300°C, pending confirmation from future geophysical surveys. On Lipari and Salina, complex hydrothermal systems have been documented. Lipari is characterised by several fluid discharges, including thermal springs, steaming ground, and a fumarole, located in the western sector of the island. The eastern sector is marked by thermal wells displaying strong mixing with seawater. In contrast, Salina shows limited surface geothermal evidence, restricted to localized submarine gas emissions and two thermal wells on the northern part of the island; the remaining samples relate to cold wells. The next planned activities include the completion of sampling on Filicudi, where only a few submarine gas bubbling sites have been identified, and the measurement of soil CO_2 fluxes at Alicudi, where no surface manifestations have been observed.

2.2.2 Geophysical survey

Geophysical surveys have been conducted to delineate the structural characterisation of the subsurface to identify the geometry and extent of potential geothermal reservoirs across the Archipelago. This objective was pursued through the application of geophysical methods, which provide crucial insights into the internal structure of volcanic systems and the configuration of the geothermal reservoirs. The geometry, depth, and fluid properties of the geothermal systems are strongly controlled by the geological and structural framework. In this context, resistivity-based techniques are among the most effective tools for imaging the subsurface features, due to their sensitivity to key physical parameters such as fluid content, temperature, porosity, and permeability (Spichak & Manzella, 2009; Ussher et al., 2000; Cumming, 2009). Magnetotellurics (MT), which analyses natural variations in the Earth's electric and magnetic fields, is widely used to reconstruct deep resistivity structures, especially in complex volcanic settings (e.g., Munoz, 2014; Di Giuseppe et al., 2023). In the Aeolian Islands, MT surveys have been performed to obtain 3D resistivity models aimed to illuminate geothermal systems beneath the islands of Lipari, Vulcano, Panarea, and Salina. On Vulcano and Lipari, 55 and 45 MT soundings were carried out, respectively. The resulting resistivity models reach depths of up to 2500 m below sea level and highlight low-resistivity anomalies associated with known hydrothermal emission areas (Fig 3). To enhance resolution in the shallow subsurface, Electrical Resistivity Tomography (ERT) profiles were also acquired in selected sectors, providing high-resolution information within the first 200 m. The integration of MT and ERT data enabled the reconstruction of the island's main structural features and the geometry of the geothermal system. To date, MT surveys have also started on Panarea and Salina islands, where data processing is ongoing. UAS magnetic surveys (by *MagArrow* magnetometer) are also currently being conducted at selected sites, with particular focus on offshore interesting sectors near the coastline.. The geophysical outputs integrated with the geochemical datasets, represent a key input for the geothermal potential assessment and numerical modelling activities. Thanks to further recent investigations related also to the volcanic monitoring and to historical data, Vulcano Island has been chosen for further elaborations able to develop 3D geological models and numerical fluid-dynamical simulations.

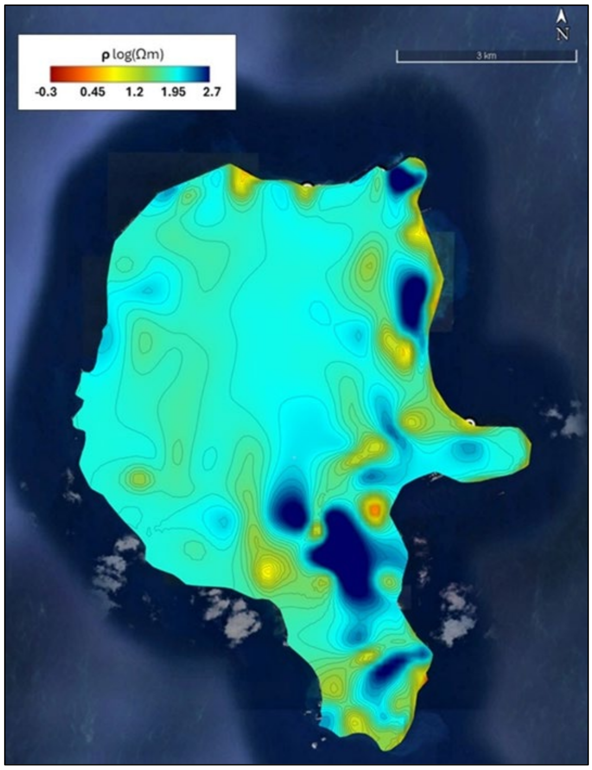

Figure 3: Horizontal resistivity section at 500 m depth extracted from the 3D model of Lipari Island. The assumed colour scale is shown.

Geological sections and well logs of the geothermal wells drilled in the past (50'-80') in Vulcano were elaborated to reconstruct a 3D geological model, identify aquifers, estimate the volume and assess thermal and hydraulic characteristics. Stratigraphic data suggest low permeability formations and intermitted fluids, except a shallow aquifer (180-600 m of depth), near to Vulcano Porto, hosted within the hyaloclastite formation and latitic lava flows, with an average temperature of 200 °C. The absence of a continuous low-permeability caprock facilitates mixing with shallow hydrothermal fluids (Sommaruga; 1984) and enables the uprising of steam and CO_2. These emissions are considered partially or entirely responsible for the degassing phenomena observed in the Vulcano Porto area. This aquifer is also clearly visible as a conductive body in geophysical investigations. A 3D numerical domain for fluid-dynamical simulations was built. The domain covers an area of 10 x 8.7 Km, 1,500 m thick (Fig. 4). Local mesh refinement was applied in key area of Vulcano Porto, including the crater conduit and the fumarolic field. The lithologies present in the selected system of Vulcano were characterised from a minero-petrographic point of view using representative outcropping samples. In particular, 14 stratigraphic units, including lavas, tuffs, and intrusive bodies, were selected and analysed by optical microscopy, BSEM-EDS, XRD, μMCT to determine texture and mineralogical assemblage. Moreover, MICP (Mercury Injection Capillary Pressure) tests were performed to define porosity, pore distribution, tortuosity, and to estimate permeability.

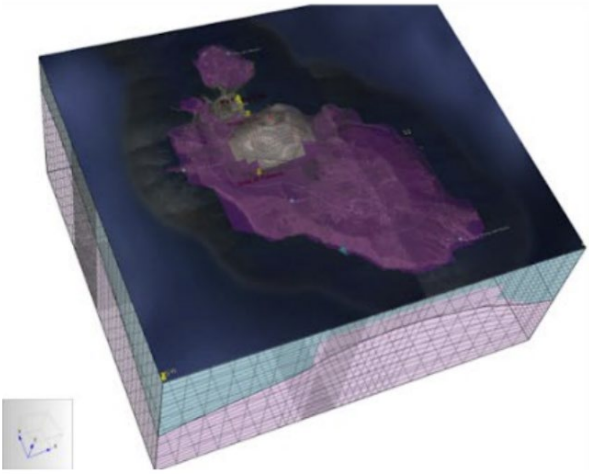

Figure 4: 3D numerical domain of the Vulcano Island, for fluid-dynamical simulations. The domain is discretized by a Cartesian mesh. Local mesh refinement was applied in key area (grey colour) of Vulcano Porto.

At steady state, the performed simulations indicate the presence of a gas-rich fluid phase (mainly CO_2) ascending along the N-S fractured system and expanding due to pressure gradients. The shallow aquifer partially buffers this upward migration of gas, allowing for the partial dissolution of CO_2. The simulated temperature distribution shows an isotherm of 200 °C located at approximately –200 meters, corresponding to the depth of the aquifer, and an isotherm of 235°C tracing the ascent of hot fluids along the N-S fracture zone. The elaborations are ongoing and detailed models are developing on Panarea and Lipari.

The preliminary results for Vulcano Island suggest that the construction of a small-scale binary cycle geothermal plant (Organic Rankine Cycle, ORC) could represent a realistic hypothesis. From the perspective of cascading the resource, the potential residual heat of the ORC plant could power a system thermal desalination (is. multi-effect distillation, MED), contributing to the production of drinking water. Moreover, among various geothermal technologies, Coaxial Borehole Heat Exchangers (CBHE) are considered, as an experimental application, for their potential to extract geothermal heat from subsurface reservoirs for direct heat uses and/or power generation with minimal environmental impact. This system utilises a heat exchanger to transfer heat between the geothermal reservoir and the working fluid within a closed-loop circuit in U-shape or coaxial configurations. These systems might be more suitable for small-scale applications or in specific contexts, such as the Aeolian Islands.

2.3 Outreach, education and social analysis on geothermal energy in the Aeolian Islands

One of the core objectives of the IRGIE project is also to enhance awareness of geothermal energy among both young people and adults, and to assess public perception and acceptability across the Aeolian Islands. Despite the significant geothermal potential of Italy, past studies outlined that public knowledge on geothermal energy is quite low and that public scepticism remains widespread, largely due to limited trust in decision makers. Previous studies (Pellizzone et al., 2017) have emphasized the importance of transparent communication and inclusive dialogue to foster greater public trust. To achieve these goals, several targeted actions have been implemented:

- Educational initiatives in local schools, including teacher training sessions and activities supported by tailored educational materials such as text for teachers (Fig. 5a-b), illustrated booklets, illustrated book for children and puzzles.

Figure 5 a-b: Educational materials developed as part of the project: a) illustrated brochure used also during

sampling campaigns and b) text dedicated to geothermal energy for training teachers and supporting the development of related activities.

- Dissemination campaigns directed at the wider local community to promote understanding of geothermal energy.
- Development of innovative outreach tools, most notably the creation of PULSE (Power Under Land, Source of Energy), a multimedia exhibit that simulates geothermal fumaroles and offers.
- Creation of interactive educational tools. In particular has been realised PULSE (Power Under Land Source of Energy), a scientific-artistic installation focusing on geothermal energy as a sustainable and renewable resource (Fig. 6). Moreover, the installation or exhibit, is accompanied by a digital platform (pulse.ingv.it) allowing users to explore geothermal topics both on-site and remotely. In detail, the web platform provides educational materials and interactive resources to foster awareness of geothermal science and its applications. The initiative aims to bridge the gap between scientific research and society, encouraging schools and communities to explore and understand the potential of geothermal energy in addressing global energy challenges (Procesi et al., 2025).
- Public engagement and through quantitative (survey) and qualitative social analysis (focus groups) with citizens and selected stakeholders.

The results obtained from outreach activities and social analyses about public attitudes related to the development opportunities of geothermal energy will be reported to the policymakers and stakeholders, bringing citizens views to the table of strategic decision-making processes.

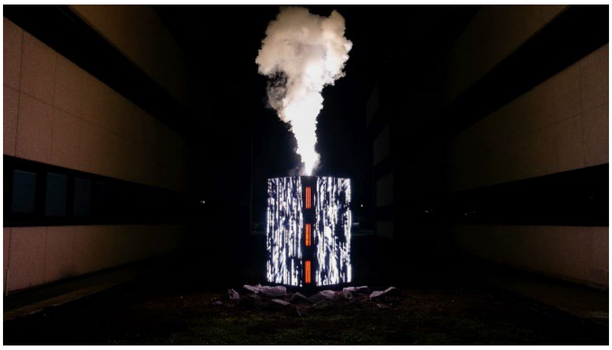

Figure 6: Scientific-artistic installation *PULSE* located at INGV (Rome). It is dedicated to the heat of the Earth, its surficial manifestations (such as fumaroles) and geothermal energy.

3. CONCLUSIONS

The IRGIE project demonstrates the potential of multidisciplinary research to support the geothermal exploration, also in the first stages. In the next year, the IRGIE project will develop detailed geothermal models for the most interesting islands of the archipelago, such as Vulcano, Lipari and Panarea, evaluating the theoretical and technical geothermal potential, assessing also site-specific geothermal applications. Outreach and public engagement activities have proven to be fundamental for building community awareness and acceptance, which are crucial for the success of future geothermal projects. The experience gained in the Aeolian Islands could serve as a reference model for similar Mediterranean and global contexts characterized by isolated, volcanic environments with energy supply challenges. Overall, the IRGIE project represents a significant step towards a comprehensive, integrated geothermal characterization of small volcanic islands, providing a robust scientific foundation for sustainable geothermal resource management.

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