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Article

The Marsili Seamount Offshore Geothermal Reservoir: A Big Challenge for an Energy Transition Model

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Abstract: Renewable energies have been the only sources recording a clear increase in total installed capacity, setting a record in new power capacity in 2020, despite the pandemic. The European Union Green Deal represents a strategy towards a sustainable economic model. In this framework, land-based geothermics has seen very limited development; however, offshore geothermics is almost completely absent in the discussion on energy source alternatives, even though it represents a real challenge for energy transition, including the production of green hydrogen. This article discusses an excursus on the activities carried out on offshore geothermal areas worldwide. We focused on the energy potential capacity of the Marsili volcanic seamount located over the bathial plain of the Tyrrhenian Basin, describing the detailed geological, geochemical, and geophysical investigations that have been carried out on that seamount since the 2000s. All the collected data have shown evidence supporting the existence of an exploitable geothermal system in the Marsili seamount consisting of a reservoir of supercritical geothermal fluids of about 100 km^3. We discuss and evaluate the actual consistence of the impacts associated with the occurrence of potential risks. We also describe the necessary further steps towards the pilot well. An important breakthrough in the short-medium term that allows for an exit from the predominance of fossil sources may come from the development of energy production derived from offshore high-enthalpy geothermal fields, especially in areas such as the Southern Tyrrhenian Sea. There is a natural clear predisposition for its exploitation combined with a low ecological footprint, which is the target objective of international agreements in the context of a blue economy strategy.

Keywords: offshore geothermal energy; Marsili seamount; energy transition model

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1. Introduction

Renewable energies have been the only sources that have witnessed records in new power capacity in 2020 despite the COVID-19 pandemic. Indeed, according to the Renewables 2021 Global Status Report [1], investments in renewables have grown for the third consecutive year. The World Economic Forum (WEF) in its recent report states that the past decade has established a strong initial momentum to transform the energy system in the decades ahead [2]. The International Energy Agency (IEA) in the Global Energy Review 2021 declares that reaching zero CO_2 emissions by 2050 requires an unprecedented clean technology push to 2030 and does not require investments in new fossil fuel supplies [3].

The European Union (EU) Green Deal (European Commission, The European Green Deal—Developing a sustainable blue economy in the European Union, COM/2019/640, December 2019) is the main new growth strategy to transition the EU economy to a sustainable socio-economic model. Its goal is to make Europe the first climate neutral continent by 2050, resulting in a cleaner environment, more affordable energy, smarter transport, new jobs, and an overall better quality of life.

It is clear that renewables are developing, but we have been discussing intermittent sources for decades (with a low capacity factor), such as wind and solar photovoltaic, and sources such as hydroelectric and biomass, which have a high water footprint of energy consumption [4]. The geothermal energy, linked to the internal heat of the Earth, is not well discussed. The Earth's energy balance is negative, i.e., the Earth loses more energy than it receives from the Sun.

Land-based geothermics, developed in Italy about one century ago, has seen promising developments, even if very limited. However, offshore geothermics is almost completely absent in the discussion on energy source alternatives, even though it represents a real challenge for energy transition, including the production of green hydrogen [5].

Volcanic areas all over the world integrate the presence of constantly refilled reservoirs of high-enthalpy hydrothermal fluids, with a capacity factor in new geothermal power plants that can reach 95% [6]. We present and discuss the energy potential capacity of the Marsili volcanic seamount located in the bathial plain of the Tyrrhenian Basin.

2. Worldwide Offshore Geothermal Areas

The amount of energy produced by actual geothermal sources is negligible if compared to the exploitable potential. Moreover, geothermal plants are all located on dry land, which represents only 25% of the Earth's surface. It is well known that the energy release from submarine volcanic areas is immense. Recent investigations of the megaplumes generated by submarine volcanic eruptions in the North East Pacific revealed that the substantial release of energy cannot be supplied by erupted lava alone, but also from the rapid emptying of reservoirs of hot fluids within the Earth's crust [7]. The use of energy released by hydrothermal fluids for offshore geothermal power generation was discussed in the 1970s, when Willliams [8] estimated that roughly one man's gross energy consumption rate was linked to the hydrothermal discharge at seafloor spreading centres and submarine volcanic areas. The author indicated several potential areas, such as the Gulf of California, the Sea of Japan, the Andaman Sea, and the Tyrrhenian Sea in Southern Italy. In the latter area, Erickson reported an average heat flow of about 3.4 HFU (heat flow unit) from an area at depths between 2.5 and 3.5 km with an average sediment thickness of 1 km [9]. The Gulf of California and the Tyrrhenian Sea were then further investigated in the early 2000s. In the former, Hiriart et al. reported that, from a medium-size hydrothermal vent at a 2000-m depth, a potential of 20 MWe of electricity can be generated [10]. In the Tyrrhenian Sea, Caso et al. in 2010 [11] estimated a total power capacity from the largest submarine volcano, the Marsili seamount, as high as 800 MWe. More recently, new areas have been investigated. In 2019, Pedamallu et al. [12] studied four hydrothermal vent fields along the Mid-Atlantic Ridge near the Azores, and estimated a power generation capacity ranging from 8.8 MWe (the Menez Gwen hydrothermal vent) to 145 MWe (the Lucky Strike hydrothermal vents field). In 2017, Prabowo at al. [13] estimated that several seamounts in Indonesia (such as Banua Wuhu, NEC, Submarine, and Kawio Barat) are hotter than the land geothermal system due to a shorter distance to the magma chamber.

Suarez-Arriaga et al. [14] explained that submarine geothermal reservoirs and their energy potential can cover significant parts of the global future energy demand in an environmentally sustainable way. This path is already practicable and economically affordable, as it uses mature technology from onshore geothermics and offshore hydrocarbon exploitation. Developing a mathematical approach to quantify submarine geothermal resources, they argue that the capacity of the Gulf of California, transforming only 1% of 1123 $MWtkm^{-3}$ of three areas in Baja California (Mexico) into electricity, is about 26,000 MWe, while the submarine geothermal system of Santorini Caldera (Greece) yields 869 MWe with an estimated reservoir of 100 km^3. In a report of the Italian Geothermic Union [15], it is estimated that, in Italy, resources at temperatures above 150 °C, which are associated with "unconventional geothermal systems" within 5 km depths and whose higher priority areas on land and offshore exceed 5000 km^2, have an estimated energy potential of about 4000 MWe, which corresponds to an efficient electrical production of 25 $TWhyear^{-1}$.

Another geothermal project developed in Iceland, the IDDP (Iceland Deep Drilling Project), carried out in the last 10 years, has demonstrated that supercritical geothermal fluids could provide up to 10 times more power, per unit of volume, than the geothermal fluids used in the conventional technology. For the same rate of inflow to the well (0.67 m^3s^{-1}), a conventional well can yield approximately 5 MW of electric power (see [16] for calculation references), while an IDDP well, tapping a supercritical reservoir with temperatures of 430–550 °C and a pressure of around 230–260 bar, may be expected to yield 50 MW of electric power [5,17]. The IDDP in 2017 reached a vertical depth of over 4500 m and a temperature of 427 °C with IDDP-2, confirming supercritical conditions in the Reykjanes field, which is recharged by seawater [18]. This well and related technology represents a significant milestone in the geothermal industry.

The exploration of those areas can be performed by studies and tools taken from the oil and gas industry, such as play fairway analysis, to find ocean rift zones that contain much of the supercritical geothermal resources on the ocean floor. In Iceland, the National Energy Authority has already granted the company North Tech Energy a permit to search for geothermal energy in two wide exploration areas in the Icelandic continental shelf, one along the Reykjanes ridge and the other off the coast of North Iceland.

In Europe, there are interesting perspectives on the development of onshore geothermal energy [19], but the potential of offshore geothermal energy in the Mediterranean basin is equally important. We focus our attention on the Marsili seamount, located in the Southern Tyrrhenian Sea (Figure 1), as it is a unique area where one of the largest heat flows of the Mediterranean Sea has been recorded. The average seawater temperature in the Tyrrhenian Basin at a depth of 3500 m ranges between 12 and 14 °C [20], while the average seawater temperature is around 4 °C at the same depth in the ocean.

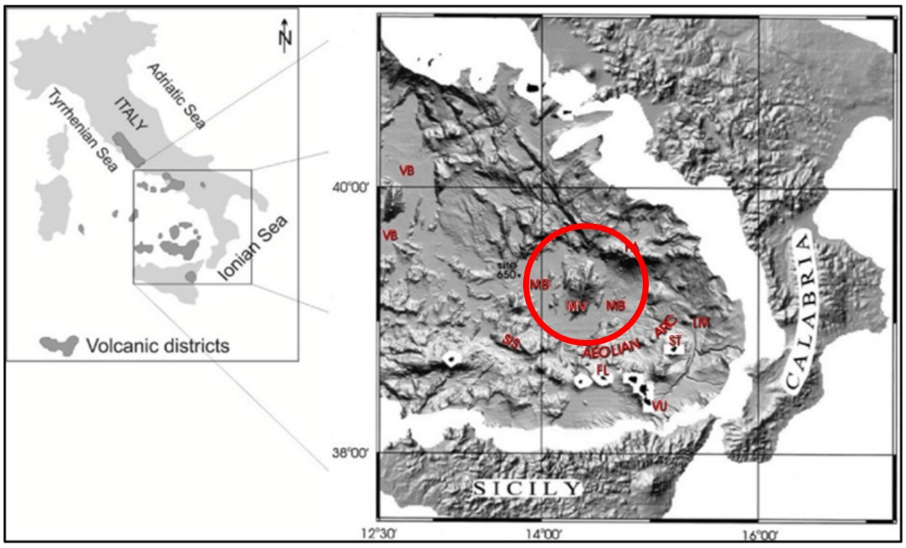

Figure 1. Location of the study area: MV: Marsili volcano and MB: Marsili basin, both indicated with a red circle; ST: Stromboli; VU: Vulcano; FL: Filicudi; SIS: Sisifo submarine volcano; LM: Lametini seamount; PA: Palinuro seamount; VB: Vavilov basin. The map on the right is redrawn from [21].

Several studies indicate that the Southern Tyrrhenian Sea presents enough evidence to be considered a large geothermal district. The area is indeed characterized by the presence of several submarine volcanic structures, which have also been studied in the past for their submarine hydrothermal systems. The Marsili seamount hosts the largest hydrothermal system and is, hence, the area with the highest potential for geothermal power generation [22].

This structure has been studied over the last 30 years and was the object of the first worldwide research permit for offshore geothermal energy (*Tirreno Meridionale 1*). The authors of this paper participated in its scientific and technical implementation.

3. Framework of the Marsili Seamount

The Southern Tyrrhenian Sea is a back-arc basin developed from the Miocene to the present above the northwestern subducting Ionian oceanic slab [23,24], characterized by a large tectonic extension inducing volcanic activity and recent diffusing seismic activity [25–29]. The Tyrrhenian Sea hosts two main abyssal plains, the oceanic crust-floored sub-basins of Vavilov (4.3–2.6 Ma) and Marsili (2 Ma) with the two greatest seamounts [30,31]. The Aeolian volcanic arc develops along the southern and eastern rims of this basin and consists of seven islands and a number of submarine volcanoes located to the west and northeast of the emerged arc [21]. Analyses on rocks sampled from these seamounts (e.g., [32]) demonstrated that those areas are affected by hydrothermal fluid circulations; in their model, cold seawater enters fractured rocks, and it is then superheated by magmatic bodies at crustal depths. Rock samples have been collected over Marsili during several dredging and coring expeditions [33–35]. The majority of those samples are basalts and, to a lesser extent, andesites and trachyandesites. Their compositions exhibit a calc-alkaline affinity, with a medium to high potassium content. The Marsili Basin, which shows remarkable similarities to the mid-oceanic ridges, has been the target of several ship-based pioneer explorations since the 1970s and has recently been interpreted as a super-inflated spreading ridge [36,37].

An extremely high heat flow with regional values in the order of 120 mWm^{-2} and a local maxima in correspondence with the Vavilov (140 mWm^{-2}) and Marsili (250 mWm^{-2}) areas have been recorded [38,39]. Furthermore, on the uppermost and central portions of the Vavilov and Marsili volcanoes, the heat flow reaches 300 and 500 mWm^{-2}, respectively [40]. Those positive heat flow anomalies coincide with the gravity and magnetic ones [41–43]. Thus, the geophysical data strongly suggest the presence of magmatic bodies intruding shallow, thinned, and stretched crustal levels. In turn, the diffuse and localized high heat flows are related to the uprising of basaltic melts at a depth below the Tyrrhenian seafloor. Therefore, volcanic Tyrrhenian seamounts can be considered large heat sources, the Marsili seamount being the most intense. The last Marsili eruptive period, marked mostly by effusive activity and low-energy explosions, is estimated between 0.78 and 0.1 Ma. Its activity is presently characterized by secondary volcanic phenomena, such as a venting of submarine fluids associated with low-magnitude seismicity induced by volcano-tectonic and hydrothermal processes [44].

4. Results

Many scientific activities, involving some of the authors of this paper, have been planned since the early 2000s. In 2003–2005, long-term geophysical and oceanographic monitoring was carried out within the EC ORION-GEOSTAR3 project, with two multiparameter observatories deployed at the seafloor 3320 m b.s.l. in the vicinity of the Marsili seamount [45]. The two observatories were equipped with a set of sensors providing long-term continuous time series of various physical measurements. The acquired time series are the longest sets of continuous data ever recorded at the Marsili Basin. The broadband seismometer recorded interesting short-duration seismic signals at frequencies larger than 10 Hz. The rich spectral contribution at these higher frequencies can be caused by liquid-supercritical fluid phase transitions of seawater, as observed in other cases at shallower depths [46]. This kind of phase transition can be explained by the hydrothermal circulation in the Marsili seamount. Gravimeter time series have shown changes in the gravity signal from its mean value. This fluctuation was simultaneous with the increase in seismic noise at high frequencies. This temporal microgravity change with the relative increase in seismic noise is associated with the presence of magmatic hydrothermal fluids [47]. Vectorial magnetometer time series have shown a decrease in the ratio of vertical to horizontal components corresponding to an increase in underneath conductivity. We interpret this behaviour of the dynamics of the Marsili seamount system in terms of the deep circulation of thermal mineralized fluids.

In 2006 and 2010, a research group from *Università di Chieti*, *Istituto Nazionale di Geofisica e Vulcanologia* and *Istituto di Scienze Marine*-CNR, explored an area over the Marsili seamount approximately 750 km^2 wide and performed several measurements, including swath bathymetry, chirp sub-bottom profiling, magnetic and gravimetric surveys, seismic monitoring with OBSs/Hs-Ocean Bottom Seismometers/Hydrophones, and seabed sampling (for details on the activities performed, see, for example, the 2006 cruise report [48]). These measurements provided further evidence that the Marsili seamount is the largest geothermal resource in the Tyrrhenian Sea. Two gravity cores containing different tephra layers were collected on the Marsili central sector at 839 and 943 m b.s.l. Stratigraphic, geochemical data and age determinations indicate that these layers of volcanic sediments represent the proximal and distal successions of the last two submarine basaltic eruptions, occurring between 3 and 5 ka [49]. As the source area for those deposits has been determined to be from the central sector of the Marsili seamount and not from a sub-aerial volcano from the Campanian and/or Aeolian Quaternary volcanic districts, this is evidence that the Marsili seamount is still an active volcano [49,50]. Additionally, the Marsili seamount also presents the highest $^3He/^4He$ ratio ever measured in the Tyrrhenian Sea, which was found at the top of the seamount [51]. This indicates that Marsili is also hydrothermally active and supported by a significant contribution of juvenile fluids. The presence of an active hydrothermal system has also been indicated by the seismic activity recorded on the flat crest of the seamount [52]. The signals are characterized by a higher frequency with respect to normal seismic noise and a surprisingly high number of non-tectonic seismic events (about 800 within a few days). The spectral content presents progressively growing energy levels in a broadband frequency range from 4 to 60 Hz. On the basis of frequency, observations can be divided into two main groups: about 720 had a frequency between 4 and 10 Hz, and about 80 had a frequency between 20 and 60 Hz [53]. The observed seismicity characterized by a frequency between 4 and 10 Hz could presumably be connected to hydrothermal fluid circulation processes, while those with a 20–60 Hz frequency could be generated by phase changes in supercritical fluid. Caso, in his master's thesis, focused the analysis particularly on seismic noise in the absence of earthquakes. Figure 2 shows an example of the power spectral density (PSD) of the seismic noise [52].

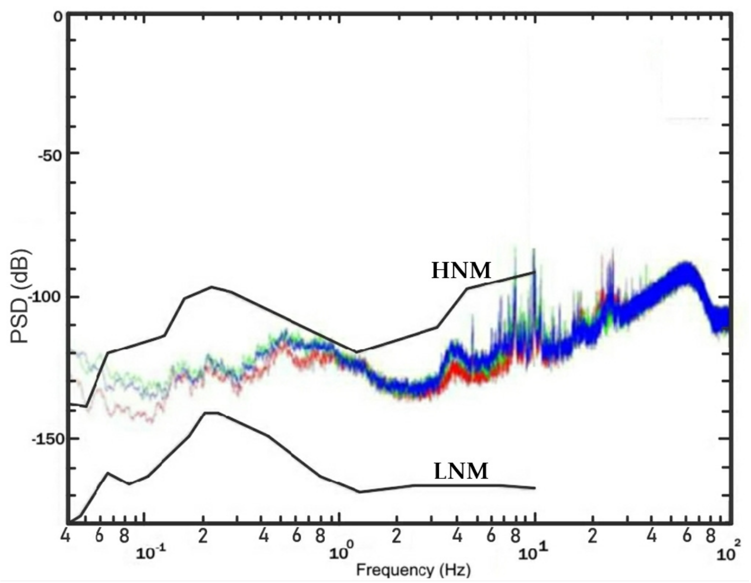

Figure 2. PSD of the seismic noise recorded by an OBS/H on 20 July 2006; 20–60 Hz peaks are well visible (redrawn from [52]). The two lines, HNM (high noise model) and LNM (low noise model), are according to [54].

A similar acoustic pattern as shown in Figure 2 is a common feature in submarine hydrothermal systems, such as that located off the island of Panarea (Aeolian Islands), where acoustic monochromatic signals peaking at 6 Hz have been recorded [55]. These signals, due to the fluid-solid resonance dynamics of volcanic conduits or fluid-filled cracks [56], also characterize several volcanic seamounts and hydrothermal areas all over the world. This "tornillos-like" acoustic noise, recorded either at Panarea or Marsili, therefore provides a significant constraint for the occurrence of ascending hydrothermal fluid dynamics (along both conduits and cracks) at the Marsili seamount. The experimental and observational indications constrain the presence of a very active hydrothermal system at the Marsili seamount marked by an intense circulation of fluids in the supercritical phase moving across fractures.

Evidence of fluids venting from the seafloor has been detected by chirp investigations, and an 80-m-high acoustic disturbance was directly observed and captured in the proximity of the seamount crest (Figure 3).

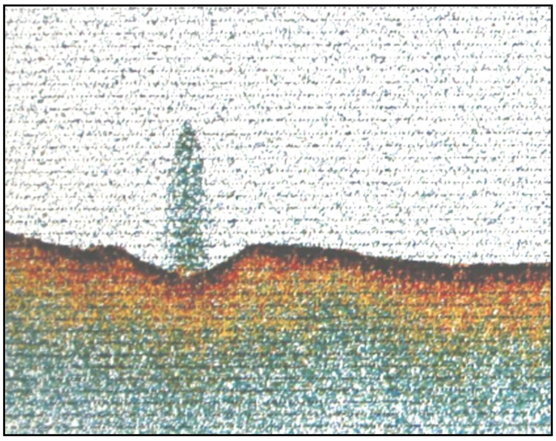

Figure 3. An 80-m-high episode of degassing in the proximity of the Marsili seamount crest recorded with chirp investigations (courtesy of ISMAR-CNR).

New gravimetric and magnetic measurements have also highlighted the very low magnetic anomaly values over the seamount crest due to the presence of rocks with very low and/or non-magnetic properties. The submarine hydrothermal activity may be a cause of such magnetic inhomogeneity. The hydrothermal fluids may interact with the source rocks and decrease magnetization by breaking down the magnetic minerals [57,58]. This evidence corroborates the occurrence of hydrothermal processes, possibly still active or recorded by geothermal deposits on the crest of the Marsili volcano [21,32]. The anomalous gravity field observed at the Marsili seamount can be fitted only assuming a mean density of the volcanic structure of about 2 gcm^{-3}. Taking into account the petrographic features of the Marsili rocks [35], as well as the magnetic data, such values can be attributed to rock porosity/permeability, possibly filled by aqueous and volatile phases. It can be inferred that the Marsili volcano could have a significant porosity, possibly more than 10% by volume. The Marsili volcanic system shows widespread hydrothermal alterations that correlate with gravity and magnetic lows. Several geophysical parameters helped to constrain the distribution of hydrothermal alteration and its relationship with both volcanic and tectonic structures, including the role played by ring complexes that favours hydrothermal circulation [59].

In a recent paper, the authors re-analyzed the geological, geochemical and geophysical feature information of the Marsili seamount collected in previous projects (2003–2005) and cruises (2006, 2007, 2010, and 2011) [60]. The aim was to collect all evidence supporting the hypothesis that this seamount can be considered a large geothermal energy resource that could significantly improve the geothermal power generation in Italy. Some of the main conclusions of that paper are as follows:

- the Marsili seamount has a shallow and strong heat source;
- an active geothermal fluid circulation is suggested by the evaluation of the permeability;
- hydrothermal fluids, as well as magmatic-type helium, are injected in the deep-sea waters, indicating that the hydrothermal activity is still ongoing;
- the presence of solid deposits of hydrothermal origin indicates that geothermal fluids permeate the edifice and are vented into the seawater.

Analysis of Potential Risks

The geophysical measurements, together with the high resolution geomorphologic data measured during the above-mentioned exploration cruise, show a large landslide crown observed in the northwestern sector of the volcano [61]. The geophysical data indeed show the most dense and locally low-magnetized portion of the volcano summit, while the geomorphologic data show features of a flank collapse. This likely exposed the most internal and central portions of the volcanic system. A recent study by the Tsunami Research Team of the Bologna University [62] hypothesised three mass failures taking place at different depths on the flanks of the Marsili volcano and then modelled the tsunamigenic potential effects in a speculative approach.

About 300 descriptions of tsunamis and similar phenomena in the Mediterranean Sea [63,64] and the Tyrrhenian coasts of Sicily and Calabria, well known tsunamigenic areas, have been made [64,65]. However, the historical and pre-historical tsunamis in these areas have been connected either to seismic activity related to the Messina Strait and Eastern Sicily earthquakes [66,67] or to landslides related to the volcanic activity of Stromboli [68]. Recent papers, one describing the tsunami effects observed along the Italian coasts [69] and a second addressing the tsunamis in the Mediterranean Sea and searching for clues of tsunamis in the geologic records and for paleotsunami deposits [70], do not indicate phenomena related to the Marsili seamount. We are confident that no evidence in the Quaternary geomorphologic and sedimentological features of the southeastern Tyrrhenian coasts points to the occurrence of tsunamis generated by collapse phenomena at the Marsili seamount.

Hydraulic fracturing in geothermal reservoirs is a well-known stimulation method used to increase production from conventional and unconventional hydrocarbon reservoirs. In recent years, hydraulic fracturing has been widely used in Enhanced Geothermal Systems (EGSs) (e.g., [71–73]). Exploitation of the Marsili volcano will involve a naturally fractured system, with no requirements for artificially generated fractures and hence no impact on the rock stress fields. The only impact is related to the near-field alterations made for the stress field during drilling, which might lead to the careful control of wellbore stability.

Another risk associated with fracturing in EGSs is the induced seismicity described by some authors (e.g., [74,75]). One analogous example of induced seismicity is one of the wider geothermal fields in the world, The Geysers in Northern California [16]. In this area, the increasing induced seismicity was indicated by the USGS as being due to the water injection used in the production process of geothermal electricity. We have to underline that there are no cases of induced seismicity by geothermal exploitation in naturally fractured reservoirs, especially in marine environments where seawater refills the geothermal reservoirs.

5. Discussion

The Earth's heat flow output is over 4×10^{13} W, an energy amount four times the present world energy consumption (10^{13} W). Only a fraction of it can be used, but very little has been done so far, especially with regard to offshore geothermal energy. This significant energy resource is ubiquitous between the land and the sea and is normally linked to the terrestrial geothermal gradient, which, on average, is in a range between 40 and 90 mWm^{-2} [19], while the heat flow reaches 500 mWm^{-2} around the Marsili seamount [40].

The most important geothermal resources are mainly confined in the sea areas on the boundaries between tectonic plates and/or in areas with a great heat flow and a thinner crust. Based on the aforementioned evidence collected in the past 50 years of volcanological and geothermal investigations in the Southern Tyrrhenian volcanic district and, especially, on the Marsili seamount, we can definitely infer elements supporting the existence of an exploitable geothermal field. The Marsili seamount characteristics as a geothermal system are briefly described in the following table (Table 1).

Table 1. Description of the Marsili seamount characteristics as a geothermal system.

Elements of a Geothermal System	Description/Evidence
Hot body	Present presumably at shallow depth, as demonstrated by: • the highest measured heat flow values and water temperatures in the area, • the first documented evidence of local and still active volcanic activity, • the active circulation/discharge of hydrothermal fluids
Geothermal reservoir	Provided by low-density, high-permeability pillow lavas, as demonstrated by: • the volcanological characteristics of the erupted basalts, • the gravimetric and magnetic anomalies detected over the Marsili seamount, comparable to alluvial aquifers, • proper thermal exchange conditions for an exploitable geothermal field (Figure 4), with an estimated volume of 100 km^3; assuming a 10% permeability, it is possible to infer a volume of geothermal supercritical fluids as large as 10 km^3, with a permanent recharge by the submarine environment
Cap Rock	Provided by low-permeability andesites and tephra (see Paragraph 3) deposited above the pillow lavas
Self-sealing	The probability of fluid sealing is very low, due to: • the absence of acid volcanism; the collected rock samples have shown a low probability of fluid self-sealing related to silica, • the abundance of basic rocks (see Paragraph 3), • the scarce presence of carbonates in the area
Recharge	Naturally provided by the surrounding seawater, with a variable height of the water column from 500 m at the top and 3500 m at the bottom of the structure

Following the scenario indicated in [76], the theoretical potential resource of ocean energy is sufficient to meet the present and projected global electricity demand. Ocean energy is highly predictable and is well suited to provide base load power. The current global cumulative installed capacity across all ocean energy technologies is only 535 MW, but the attention is now mainly concentrated on wind, solar, and wave sources. Substantial growth in the deployment and installed capacity of ocean energy is expected in the coming years.

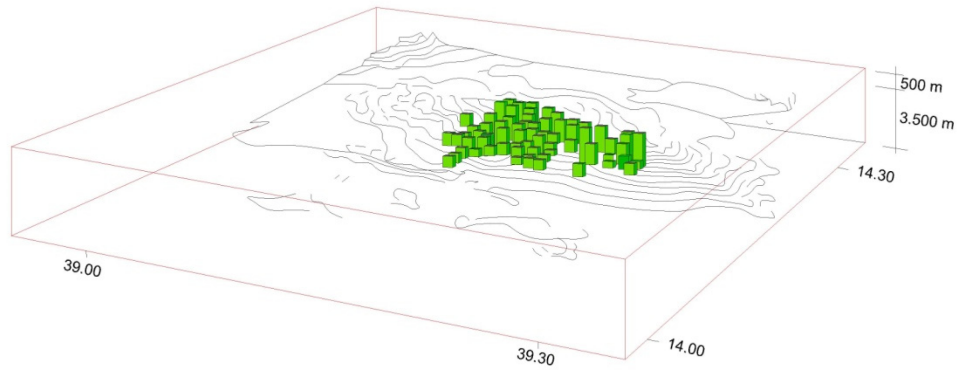

Figure 4. 3D inversion model of the magnetic anomaly field with the geometric reconstruction of the Marsili geothermal reservoir (a 100 km^3 estimated volume) (courtesy of INGV).

Renewables, including onshore geothermal resources, are not adequate to provide the amount of energy balancing that the future needs. Attention is turning to supercritical geothermal resources, and the most significant ones are the supercritical reservoirs under the ocean floor.

According to [5], a solution to the global need for base load renewable power and other economic outputs can be achieved through four inter-related fields of innovation, which adapt and develop existing technologies to use supercritical properties of geothermal resources in the deep seafloor:

- supercritical generation of base load electricity that is flexible and conveyable;
- supercritical water electrolysis for green hydrogen;
- desalination to produce bulk water;
- the extraction of minerals from the geothermal resource.

Geothermal offshore energy could provide enough base load electricity to replace fossil fuels and nuclear power as the primary sources of electricity and transportation power.

According to some authors [77,78], the electricity produced from onshore geothermal resources strongly supports the reduction in both fossil fuel consumption and CO_2 emission into the atmosphere. This is further increased in offshore geothermal resources, where, with updated technological measures, there are no emissions into the atmosphere.

The following considerations highlight that, compared to scenarios of energy from the ocean, offshore geothermics could determine a revolution in future energy scenarios. The Marsili seamount, where important geothermal activity and a large geothermal reservoir have been highlighted [59], represents a context where technical and economic conditions for investing in the exploitation of the first offshore geothermal field seem favourable.

Pending the construction of the first pilot well on the Marsili, the vast, indirect information available allows us to define a reasonable scenario for a first offshore production platform with a total capacity of 0.8 GWe. We expect to exploit a supercritical fluid with almost 400 °C and 200 bar within the reservoir [79]. By 2020, the total installed power of onshore geothermal in Europe was 3.3 GWe, for a total of 130 power plants located throughout the continent. The first offshore geothermal platform on the Marsili alone could therefore produce 25% of all geothermal energy produced in Europe and would double the current Italian capacity.

The gross efficient generation power in Italy, at the end of 2020, was equal to 120.42 GW, 56.59 GW of which were from renewable sources (47%) and 64.78 GW of which were from non-renewable sources (53%) [80]. Recent estimates on wind production in Italy show that the 5725 active turbines of various nominal power produce approximately 30 TWhyear^{-1} of electricity. The exploitation of the Marsili geothermal field has been estimated at 6.4 TWhyear^{-1}, taking as a reference the average capacity factor of high-enthalpy fields onshore geothermal plants, rated between 85 and more than 90%, depending on site conditions and plant design [81]. This value would alone represent around 35% of all wind production and around 28% of the total electricity production from photovoltaic plants in Italy [82]. It is not easy to estimate the energy potential of a geothermal reservoir, but it is important to underline that the production potential of geothermal fields is often limited by the presence of the fluid rather than of the energy stored [83]. The constant refilling of the Marsili seamount reservoir can guarantee the greater reliability of its geothermoelectric production. These figures alone make us reflect, regarding the scalability, on the efficiency and determine the difference in the environmental impact and ecological footprint between the exploitation of high-enthalpy offshore geothermal energy, such as the Marsili geothermal field, and the pervasiveness and more complicated management of other renewables plants, particularly wind and photovoltaic systems. Taking into account the Energy Transition Index (ETI) [2], Italy still occupies an important position (27 out of 115 nations) with an ETI of 66/100, which defines not only the performance of its energy system but also its readiness for a transition to a secure, sustainable, affordable, and reliable energy future.

There is no doubt that renewables in recent years represent the energy sources where most investments have been made, with a prevalence for solar and wind power, and forecasts for future investments are currently substantially linked to photovoltaic and wind power [84]. Moriarty [85] argues that current renewables would not be sufficient to substantially reduce the ongoing climate changes.

The high-enthalpy offshore geothermal source of the Marsili seamount represents a real challenge, not only because of its geothermal capacity factor of over 90% but also due to the large heat flow of this area, associated with the known favourable effects of geological, lithological, and tectonic controls, following the catalogue of geothermal play types introduced by Moeck [86]. The great importance of geological-structural factors that can allow for a profitable use of high-temperature geothermal resources for power generation has been recently highlighted in [87,88].

Presently, there are technological, environmental, and economic conditions for the offshore geothermal energy to allow new models of energy transition from fossil sources. We want to highlight the sustainability of an offshore geothermal project on the Marsili seamount, through an initial assessment of the reference parameters relating to the installation costs of the plants (Figure 5) and the scenarios of electricity production and global LCOE (Levelized Cost Of Energy; Figure 6). The basic reference of the scenarios is taken from [76,81,84]. It can be estimated that, with the same technologies adopted, the capacity factor of the production plant linked to the Marsili seamount is of the order of 90%. There is still no direct experience of exploitation of high-enthalpy offshore geothermal fields, as in the Marsili seamount. It is therefore not possible, in the absence of drilling a pilot well, to accurately evaluate the transmissivity values of the reservoir and the effective usable flow rate of the supercritical fluid, with a consequent indication of the thermoelectric production rate. According to [87], on the electric production of geothermal reservoirs with temperatures below 200 °C in EGSs, and to [88], on the relationship between permeability and porosity in geothermal reservoirs, all these systems can yield significant electric productivity.

This potentiality is even more significant in supercritical resources on the ocean floor [5]. As a rough estimate, assuming for the Marsili geothermal field a well-head supercritical fluid at around 400 °C, a 10 bar pressure, and mass flows in the range between 20 and 100 kgs^{-1} per group of interconnected wells, the theoretical power output is consistent with the 10–50 MWe range, thus confirming the preliminary estimates of total capacity. These estimations represent flow conditions comparable to those found in wide-area on-shore geothermal dry steam fields, such as The Geyser field in the US.

From an energy density perspective, it is worth observing in a geothermal field such as Marsili that 1 km^3 of basalt bodies (a density of 3.1 kgm^{-3} and a heat capacity of 840 $Jkg^{-1}\,°C^{-1}$) at 1000 °C located under the reservoir carries a heat content of about 690 TWh_{th} if completely cooled at sea temperature.

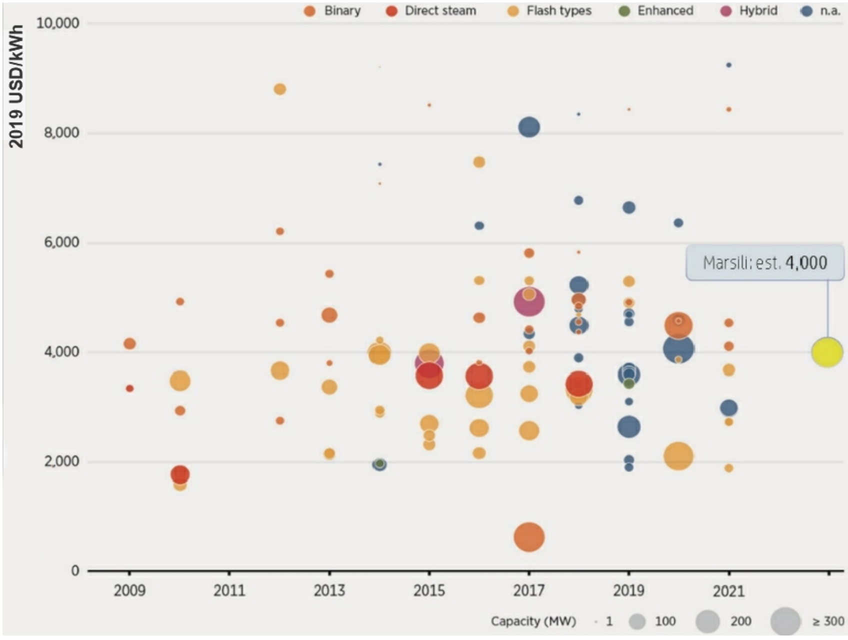

Figure 5. Geothermal power total installed costs by project, technology, and capacity (redrawn from [81]). Marsili is among the medium–high values, value estimated in 4000 USDkW^{-1} (the circle filled in yellow).

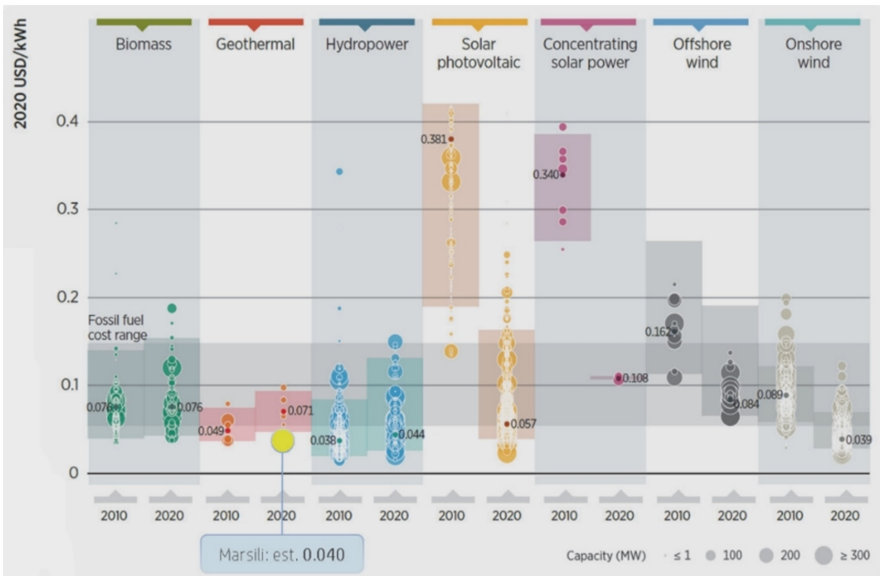

Figure 6. Global LCOE (Levelized Cost Of Energy) of newly commissioned utility-scale renewable power generation technologies, 2010 and 2020 (redrawn from [84]). Marsili LCOE is among the lowest values in comparison with other renewable energy sources, the estimation is 0.04 USDkWh^{-1} (the circle filled in yellow).

Regarding the Marsili power plant's unitary overnight cost capacity and LCOE, it is difficult to formulate a proper estimate, as there are no previous demonstrations of such a technology, and the temperature and pressure/fluid flow data considerably impact the kind of thermodynamic cycle and ultimately the equipment of the power plant. Following the trend of large geothermal power plants in recent years, we hypothesize that a Marsili prototype power plant would be located among the medium–high values of the unitary overnight cost range in the order of 4000 USDkW^{-1} (Figure 5). By using this overnight investment cost and the estimated energy production values of Marsili over a 30-year time horizon, we obtain an estimated LCOE to the order of 0.040 USDkWh^{-1} (Figure 6).

Even if the most suitable technology for the cultivation of the Marsili geothermal field will be adequately defined after a characterization of the supercritical fluid, its flow rate, and the peculiarities of the geothermal system, the above estimates are reliable as an order of magnitude and demonstrate the maturity of this project and its economic sustainability.

It is also possible to consider scenarios of green hydrogen production, both through direct electrolysis processes enhanced by high-temperature fluids and by using the electricity produced. These opportunities still require dedicated studies that go beyond this paper, while the possibilities for the exploitation of rare earth, minerals, and metals concentrated in the extracted fluid are more realistic [89].

The importance of the Southern Tyrrhenian Sea area concerning its geothermal potentiality is also highlighted in the map of a global suitability for geothermal power plant installation (see Figure 3 in [90]).

Since the technical-economic and performance feasibility of the Marsili pilot project has its own foundation, also thanks to the various offshore geothermal initiatives indicated in this paper, the low environmental footprint of the project must also be considered with respect to other renewable energies. It should be borne in mind that, to produce the same amount of energy hypothesized in the first step of the Marsili project (6.4TWhyear^{-1}), it would be necessary to use an area of about 100 km^2 for a photovoltaic system, slightly less than the urban area of the city of Turin, while about 1900 wind turbines of 1.5 MW would be needed to produce the same amount of energy with wind.

6. Perspectives and Conclusions

As already underlined above, there is a need to drill a pilot well to confirm the characteristics of supercritical fluid and the flow rate production. To locate the pilot and to define the technologies suitable for the drilling, the following is also necessary:

- Detailed investigations of acoustic noise;
- Verification of the structural and functional models of the geothermal field;
- Verification of the state of thermalism as a function of the temperature of the fluids;
- A detailed seismic-tomographic survey.

The development of offshore geothermal energy production is important for energy scenarios. The Marsili geothermal field can become the first offshore laboratory of geothermal power production for an energetic transition. This is possible due to the recent enhancements in drilling technologies operating at a high temperature and pressure. The methodology of this experiment could be applied as a case study for other offshore areas, including mid-ocean ridges.

We have started some tests to compare spectra generated at a dedicated industrial plant by supercritical fluids for the precipitation of chemicals with those recorded at the summit of the Marsili seamount. The first results of these tests have shown comparable peaks. This encourages us to continue these series of tests in a more structured way to confirm these similarities.

Regardless of what the technological model of supercritical fluid management will be, there are serious possibilities for the extraction of metals and other chemical elements that are particularly sought after for the industry.

An important breakthrough in the short-medium term that allows for an exit from the predominance of fossil sources in a sustainable, effective and resilient way may be able to be developed from energy production derived from offshore geothermal fields, especially in such areas as the Southern Tyrrhenian Sea. There is a natural clear predisposition for its exploitation combined with a low ecological footprint when it is considered from a comprehensive life cycle evaluation point of view, which is the target objective of international agreements about climate change policies. To this end, and for the sake of a rough comparison, it is worth observing that the quantity of energy needed to heat 1 km^3 of basalts from ambient temperature to 1000 °C would be of the same magnitude of the

2020 electric production of all of the European intermittent sources (wind and photovoltaic) transformed into heat (around 604 TWh).

Starting from an important knowledge base of the geothermal context of the Marsili seamount, additional, more recent data have confirmed that this seamount represents a geothermal field of considerable value, with all the preliminary conditions for being exploited.

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