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Synergic and conflicting issues in planning underground use to produce energy in densely populated countries, as Italy
Geological storage of CO_2, natural gas, geothermics and nuclear waste disposal

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HIGHLIGHTS

- ▶ In densely populated countries, the public need a synergic approach to produce low-carbon energy.
- ▶ The paper is mapping coexistent and different underground technologies to produce low-GHG energy.
- ▶ The paper calculate Energy Density Potential in Land – EDPL in terms of [GW h/ha/year].
- ▶ Draw-plate technologies platforms (EU-ZEP, etc.) should merge using underground together.
- ▶ Synergies among the different uses of deep underground (up to 5000 m) jointing the energy lobbies.

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ABSTRACT

In densely populated countries there is a growing and compelling need to use underground for different and possibly coexisting technologies to produce "low carbon" energy. These technologies include (i) clean coal combustion merged with CO_2 Capture and Storage (CCS); (ii) last-generation nuclear power or, in any case, safe nuclear wastes disposal, both "temporary" and "geological" somewhere in Europe (at least in one site): Nuclear wastes are not necessarily associated to nuclear power plants; (iii) safe natural gas (CH_4) reserves to allow consumption also when the foreign pipelines are less available or not available for geopolitical reasons and (iv) "low-space-consuming" renewables in terms of Energy Density Potential in Land (EDPL measured in [GW h/ha/year]) as geothermics. When geothermics is exploited as low enthalpy technology, the heat/cool production could be associated, where possible, to increased measures of "building efficiency", low seismic risks building reworking and low-enthalpy heat managing. This is undispensable to build up "smart cities". In any case the underground geological knowledge is prerequisite.

All these technologies have been already proposed and defined by the International Energy Agency (IEA) Road Map 2009 as priorities for worldwide security: all need to use underground in a rational and safe manner. The underground is not renewable in most of case histories [10,11]. IEA recently matched and compared different technologies in a unique "Clean Energy Economy" improved document (Paris, November 16–17, 2011), by the contribution of this vision too (see reference).

In concert with "energy efficiency" improvement both for plants and buildings, in the frame of the "smart cities" scenarios, and the upstanding use of "energy savings", the energetic planning on regional scale where these cities are located, are strategic for the year 2050: this planning is strongly depending by the underground availability and typology. Therefore, if both literature and European Policy are going fast to improve the concept of "smart cities" this paper stresses the concept of "smart regions", more strategic than "smart cities", passing throughout a discussion on the synergic and conflicting use of underground to produce energy for the "smart regions" as a whole.

The paper highlights the research lines which are urgent to plan the soundest energy mix for each region by considering the underground performances case by case: a worldwide mapping, by GIS tools of this kind of information could be strategic for all the "world energy management" authorities, up to ONU, with its Intergovernmental Panel on Climate Change (IPCC), the G20, the Carbon Sequestration

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Leadership Forum (CSLF) and the European Platforms such as the "Zero Emissions Fossil Fuel Power Plants" (EU-ZEP Platform), the Steel Platform, the Biomass Platform too. All of these organizations agree on the need for synergistic and coexistent uses of underground for geological storage of CO_2, CH_4, nuclear waste and geothermic exploitation.

The paper is therefore a discussion of the tools, methods and approaches to these underground affecting technologies, after a gross view of the different uses of underground to produce energy for each use, with their main critical issues (i.e. public acceptance in different cases).

The paper gives some gross evaluation for the Lazio Region and some hints from the Campania Region, located in Central Italy. Energy Density Potential in Land (EDPL), is calculated for each renewable energy technology (solar, wind, geothermal) highlighting the potentiality of the last.

Why the Italian case history among the densely populated countries? on the Italian territory is hard to find suitable areas (mostly if greenfields) to use the own underground, with respect to other European countries, due to the presence of seismotectonic activity and many faulted areas characterized by Diffuse Degassing Structures (DDSs, which are rich in CO_2 and CH_4). In this cases, public acceptance must be facilitated by the concerted efforts of researchers, universities, NGOs and policy-makers.

1. Rationale

The worldwide demand for energy has grown so much that there is the need to develop a strategic mixed-energy plan. Such a plan should follow the IEA Road Map 2009 (see www.iea.org and its improvements as the IEA Workshop "Monitoring Clean Energy Economy", 16–17 November, 2011, Paris, www.iea.org, which follow the first International School in Erice about a synergic approach to a multi-face sound energy mix, using underground too [1]). This multi-component approach to the energetic use of underground (0–5000 m depth) is fundamental to solve the problem of "low carbon" energy production, namely to reduce the increased CO_2 emissions. The main sources of anthropogenic CO_2 are from industrial processes, transportation and residential and commercial buildings. The most urgent reduction need is that of CO_2 emissions from the coal-power generation industry. A study published in 2006 by the European Commission [2] shows that if existing trends continue, CO_2 emissions will be unsustainably high by 2050 – that is, CO_2 concentrations will be 900–1000 ppm by volume. This affects abruptly the climate changes. Also the recent climatic and weather episodes such as the "big cold" during the first days of February, 2012 are considered as a consequence of North Pole climatic effects (www.NOAA.gov). At present, literature is full of papers before and after this mentioned report, highlighting the urgency to find remediation to the energetic–climatic crisis. Now is time to "do".

Recent studies are dealing with power management systems planning under uncertainty and management of composite electric power systems [3] considering the complex multiple electric power generation patterns, considering and the security-failure risk assessment, which unfortunately does not include the geological ones [1].

A variety of complexities are associated with power management systems together with multiple forms of uncertainties: literature up to date does not consider enough those associated with underground resources, reserves, capacity and intrinsic risks. Moreover, when the renewable energy is considered, very often the geothermics are not mentioned (as in [3]). The importance of geothermal energy is growing worldwide and it is not possible to take off from the evaluations (www.egec.org, www.geothermalcommunities.eu).

It is very difficult for decision-makers to single out optimal decision alternatives for cost-effective power generation and therefore it is desired to develop affective tools to support the planning of power management systems [3]. However in densely populated countries, as Italy, where the NIMBY (Not In My BackYard) and NUMBY (Not Under My BackYard) syndromes are predominant, the problem are not the technology-costs, but the planning pass through the more difficult obstacle of public acceptance. It is a paradox but it is more difficult to find the best heuristic approach [21] (Quattrocchi and Boschi, 2011, www.terrascienza.it) [48] to a public communications of the risk with respect to schedule algorithms for identifying potential decision alternatives of power generation companies within a liberalized market.

The actual literature does not considered enough uncertainties existing in the real-world power generating activities i.e., the geological ones, such as reserves, supply, storage capacity, technology development, M&V limitations. The emphasis in literature is too much focused on "costs", but the real obstacles are linked to sociological and political aspects: how much the citizens trust in good science and technology.

Geological variables, as number of possible earthquakes generated by fluid overpressures due to geogas storage activities or the area possibly affected by CO_2 or methane leakage at surface and indoor could not be canalized together with other concepts as possible stochastic linear optimization programming into the management of power generation (see references in [3]).

For geological choices to select the final use of a portion of deep underground or adjacent deep geological structures, there are more than difficulties in analysing economic consequences due to the violation of relevant policies in irreversible resources, with enormous implication in environmental liability and management, including the role of colossal private assurance companies.

If we consider the underground-linked power generation technologies (reserves, storage space, faults, etc.) the time-patterns for decisions are too much longer and completely different with respect to other power generation technologies: years instead of months, as order of magnitude of time scale to take final decisions. In cases when the underground is not involved, routinely, according to the social and geographic features of a specific region, multiple electric energy resources are considered to satisfy the electric power demand and guarantee the safety in power supply: literature very rarely considers the case histories where the deep underground is involved. Very often the bar-chart and scheduling of interactive relationships among subfactors within a power generation management system do not consider the interactive relationships among peculiar subsystems, such as underground availability, where also the geological part of the problem is involved within a power management system itself. It has routinely complex interactions – with the external subsystems (including residential living, economy, policy and environment, mass balance energy resources, mass balance for plants capacity) and balance between power fuels supply and demand. Any change in one subsystem, with its time-dependent processes (i.e., permits and allowances for the underground use) will cause the variations of others subsystems (time-dependent by the longer process, as the acceptance of the underground use), and finally vary the economic, environmental and social costs. An example is the decision of the underground risks liability, if public (State, Region, Municipalities) or private (companies, assurances). For example, the underground/ environment policy drew out by local more than national government can change a series of decisions involving electric energy resources, energy related technologies and final electric generation and usage, more than other factors (i.e., costs of fuels, cost of terrains, capital costs instead of monitoring/waste storage costs). At the same time, the political–social-economic power is changing, i.e., in Italy every 4 years or less, therefore before the underground-related decision [29] should complete a single permission paths, further adding uncertainties and impacts to the final optimal decisions in power system planning.

Energy storage, waste storage and heat availability: these underground uses are difficult to be inserted in interactive relationship schemes between external systems and a power management system, mostly if we remain to the space scale of "cities" within the IMRP approach (Interval-parameters Minimax Regret Programming [3]) and not to the space scale of "regions", as we stress in this paper. Only by thinking in a regional Scale we could overcome the complexities and uncertainties of the power system which increase the difficulty level of determining the optimal energy plan strategy. We have to start to define regionally the "energy potential in land" in terms of [GW h/ha/year] for each used technologies considering the land/underground availability and the demand on national level as a whole as well considering the CF (Converting Factor) as the ratio of the amount of power electricity obtained [PJ] to the amount of facility capacity [GW].

This paper intends to be a discussion, and not a review, nor a detailed description of each energy-related underground use as a whole: the paper is aimed to hint some ideas and methods to better decide about the use of underground to produce "low carbon" energy on a regional scale, in densely populated areas.

We stress the importance to evaluate the synergies and/or conflicts between important technologies that can produce clean energy and that involve at the same time the use of deep underground, namely the deep geological reservoirs. They were used in the past to produce hydrocarbons and now are generally depleted or disused. This is a strategic prerequisite to plan regionally a sound and equilibrated mix to produce energy. Recently a big emphasis is given to the concept of "smart cities" while in this paper we restore and introduce the concept of "smart region": a wider region with respect to those pertaining to "smart cities", including the regional underground reservoir for energy storage, "energy produced waste" storage and heat production towards energy and enthalpy.

The discussed technologies include:

- clean coal power plants combined with CO_2 Capture and Storage (CCS) technology (e.g., EU-ZEP Platform, EERA-CCS framework, CSLF web sites as a whole) [4];
- natural gas (CH_4) storage in depleted reservoirs or in saline aquifers [9,10], as strategic reserves to be readily available during failures or stoppages of pipelines from abroad;
- last-generation nuclear power plants (e.g., EU Nuclear Platform), not necessarily in all the European countries, namely selected as a function of the geodynamical safe conditions (mostly after the Japan crisis), with at least one European safe HLW geological disposal, associated with a lot of national "near-surface" provisory nuclear waste disposal sites in each country;
- renewable energy sources, possibly including low-space-consuming technologies such as deep geothermal energy (i.e., the new generation of technologies for high-to-medium enthalpy, e.g., EU Renewables Platform, EERA framework).

All of these drawing-board technologies are already proposed and defined by the International Energy Agency (IEA) Road Map 2009 as priorities for worldwide security. In concert with "energy efficiency" and the upstanding use of "energy savings", these goals are strategic for the year 2050. These priorities are urgent for all the "world energy management" authorities, such as the ONU, the Intergovernmental Panel on Climate Change (IPCC) [4], the G20, European Platforms such as the "Zero Emissions Fossil Fuel Power Plants" (EU-ZEP Platform) and the Carbon Sequestration Leadership Forum (CSLF) [3].

All of these organizations agree on these priorities, but only recently the scientific community become involved in the dialog on the need for synergistic, coexistent or conflicting uses of underground geological structures (mostly if capable for more than one purpose) for geological storage of CO_2, CH_4, nuclear waste and geothermics exploitation. This discussion involves political frameworks in fast evolution during the actual energetic–climatic and economic crisis ongoing (see web link of the Public Hearings of Quattrocchi at the European Parliament, on April 14, 2010, http://www.eppgroup.eu/Press/peve10/eve009pro_en.asp).

In turn, any underground storage, addressed to produce energy needs "public acceptance", which includes stages of "public awareness" and "public ownership" of the "underground space", for storage and geothermal uses.

The best results are obtained when the communication and involvement with the local population for each project begins early in the process, i.e. by creating "observatories" [17,21–23]. One sound example is the "Osservatorio CCS" in Italy (www.osservatorioccs.org) pertaining to the CO_2 Capture and Storage improvement in Italy.

Underground gas storage (both CO_2 and CH_4) and deep geothermics are challenging multidisciplinary research fields, that not only include the Earth Sciences (such as environmental science and reservoir-mining engineering) but can also be linked with economics and social sciences.

We intend to discuss in this paper to find both common arguments and differences in Earth Science between the different uses of deep underground, namely geogas storage, nuclear waste storage and geothermics. Information coming from geothermal variables could be used for CCS exploration and viceversa [18].

In particular, the merging of mass-transport, geochemical and geomechanical numerical modelling is particularly challenging and fulfilling.

In this paper we try to give hints about the organization of a common geo-referenced data-base on GIS platform (after [19,20,24]) to be delivered to the regional authorities, including all data necessary to the parallel calculus in numerical modelling of both the 3D Earth Modelling of entire crustal blocks as well as mass-flow reactive/geomechanical modelling of the storage reservoirs. Currently, this is the main gap that should be filled for effective underground reservoir characterization and risk assessment (i.e., geomechanical conditions of caprock, leakage from reservoir, induced hydro-fracturing and seismicity, dynamic capacity of the structures, etc.

The modelling of the behavior of a geogas, as CO_2, which is also reactive [5–8] completely modifies the previous "inert" mass-transport un-reactive modelling of natural gas as standard oil-companies reservoir engineering know how since the sixties.

The 3D-Earth Modelling is, at present, in advanced level in Italy, which is located in one of the most complex world's seismotectonic settings as mentioned. Thus, it could be a good training site [9–11]; for other countries: this paper has the aim to resume the GIS geo-referenced objects, not only the geological ones, but also those useful for any kind of underground use, addressed energy production. In particular, the modelling of fault zones in a multi-disciplinary geophysical and geochemical approach [after 9–11,21], both seismogenetic and not. Information layers on faults are typically strategic powerful strata, coming from our Earth Science scientific community: if the information is associated to knowledge about fault-related hot/supercritical/cold filling fluids (with their consequent possible fluid leakage at surface) it is a challenging field of research for any underground use, both storages and geothermics [11–16]. Geothermal potential is mostly concentrated along faults [24–28]. Seismotectonic, structural and geochemical disciplines need to be strongly integrated to proceed from CH_4 storage to CO_2 storage, associated to geothermics too. Geothermal exploitation should be focused on target of explorations that was initially address only to geological CO_2 storage [9,10,17–21]. These two uses of underground could coexist at different levels of the crustal blocks (i.e. see the Niels Christensen lecture at the GZF-Potsdam workshop in 2010 dedicated to Geothermal Energy and CO_2 storage, Synergy or competition, http://www.gfz-potsdam.de/portal/gfz/Neuestes/Veranstaltungen/Tagungen+und+Konferenzen/2010-Conferences/100210-11-GeothermalEnergy-and-CO2-Storage). This paper is addressed to discuss these aspects.

Some areas could be efficiently exploited in a multilayered manner (i.e., CO_2 storage at 1500 m depth and a binary-cycles at 3000–5000 m depths, injecting CO_2 could be a typical scenario [30]). Conversely, an area affected by underground CO_2 or CH_4 plumes would be off-limits for centuries as a destination for nuclear waste disposal (either geological or at shallow depths such as "near-surface" types) as well as for "nuclear power plants location", strongly affecting the "infrastructures siting". This criterion, which take in consideration the underground gas storage and geothermics is not yet inside the IAEA criteria as a whole and they should be inserted as soon as possible, otherwise we could risk to locate a sound site for infrastructural plants where a very good site for underground gas storage is located (i.e., Padana Valley in Italy).

In densely populated countries, the problem is amplified to produce "low carbon" energy. In this case, mostly in Italy, which is full of mountains and geodynamically young, the prerequisites, as mandatory are: (i) underground space for storage and geothermal exploitation, (ii) water at the Earth's surface, (iii) public acceptance, and (iv) scientists in-staff dedicated to each technology (fewer and fewer students have been present in Italy in recent past).

A new tecno-political approach to the problem is also needed that will joint (and not divide) the different stakeholders and the scientific community: these stakeholders are currently linked to the different and separate priority-setting boards (i.e., European Platforms); namely the "Renewables Platform", is completely separated by the "EU-ZEP Platform" or by the "Biomass Platform" or by the "Steel Platform". European Parliament and authorities urgently have to joint, by plenary sessions the different European Platforms, first of all the EU-ZEP and the geothermal-renewable one. This paper discusses the possible themes for this kind of plenary technico-political sessions. A previous example of the link between different technologies is a "Position Paper" of the EGEC (European Geothermal Energy Council, December 15, 2009) that recognizes the need to identify synergies and conflicting issues (i.e., between CCS and geothermics, [30]) and to attempt to build collaboration around areas of common interest among the previously mentioned communities; such efforts will decrease costs and jointly resolve environmental issues.

With a worldwide population of seven billion people, the safe use of the geological underground will become increasingly important. Geophysical and geochemical risk assessment is a prerequisite and mostly concerns induced seismicity and surface leakage of geogas and/or steel-insulated radio-nuclides injected industrial fluids, such as CO_2 and CH_4 [21]. Unfortunately, the time we are allotted to address the issues of climate change and the exhaustion of reserves is short, and we must adopt a "learn by doing" approach (especially for CO_2 storage) [21].

One of the question of the paper is what use of underground must have the priority?

CCS is a bridge technology, but considering the enormous exploitation of coal undertaken recently without CCS, to produce energy in India and China, it is particularly urgent with respect to the other uses of the underground space. The paper starts to discuss how to reach this target by storing CO_2 but at the same time help the rest of the underground uses: such as the use of CO_2 as cushion gas during natural gas storage. A fully carbon-free technology sufficient to replace fossil fuels (advanced nuclear included) is still far off.

Governments could utilize CCS not only to meet the lowered emission targets but also to offset costs by using the CO_2 to increase hydrocarbons production (EOR = Enhanced Oil Recovery and EGR = Enhanced Gas Recovery). At the same time the differences and synergic underground uses require a common discussion about energy infrastructures at surface such as pipelines and a map of the possible energy production intensity in terms of [GW h/ha/year] [22,23] considering that for each technology there is a conversion factor to pass from [PetaJoule] to [GigaWatts] [3].

Deep geothermics is a promising technology that can be applied in a "hot" country such as Italy and along some peculiar fault systems that have been discovered by fluid-geochemical methods [12,13,24–28–42] but these sedimentary basin hosting deep saline-hot aquifers, could be the same sedimentary basin need to natural gas storage.

Geothermics allows for extracting power or heat from the ground; however, cost evaluations are subject to either a scale factor and or an externalities assessment, i.e., oil companies could support the exploration phase if the final destination of the exploratory drilling includes both gas storage and geothermics and not only... geothermics. If widely deployed, deep geothermics (i.e., Deep Geothermics – DG – such as Enhanced Geothermal Systems and binary cycles) could contribute to meet energy demands without additional CO_2 emissions, but the underground used for these projects should be cast-off before to CO_2 storage, which is more urgent than geothermics in some geopolitical visions [2].

DG and CCS technologies are linked by a common feature; they both have great impact underground and above ground. Consequently, relevant territorial and infrastructure risk analyses and mitigations are required. Given the urgency of the situation, deployment of CCS and DG must begin with the most promising technology currently available. The oil and gas industries already run large chemical plants that are similar (although different in scale) to some types of CO_2 capture facilities fit for power generation. DG could begin exploring extensions of well-known geothermal heat-pump technologies [1].

An inverse correlation between environmental taxes (i.e., a desirable Carbon Tax) and emission patterns for the overall economy is widely recognized; thus, macroeconomic links and constraints must also be considered and evaluated. This requires implementation of modelling tools that aim to produce accurate sensitivity studies so that optimal infrastructure patterns can be defined [33].

Social costs also must be taken into account, beginning with public acceptance. This requires dedicated efforts and activities (such as those that INGV has undertaken in the last 10 years) [17,21] that merge geological, industrial, national and environmental data.

In summary, for this paper, it is imperative to start to identify and discuss possible synergies, compatibilities, conflicting issues and causes of positive and negative interference among the different uses of underground areas (500–5000 m depth) for energy production technologies in industrial and densely populated countries and, on the contrary, perform the "infrastructure siting" with an eye to the underground potential.

2. Methods and results

2.1. Teaching – public outreach

The common Tor Vergata University-INGV strategic teaching activities (including beginning courses, degree theses, PhD theses, meetings with NGOs, stakeholders, policy-makers and visits to power plant infrastructure) aim to merge various low-carbon electric power production technologies, by spreading the knowledge about the safe and synergic use of the common and precious underground space in densely populated countries such as Italy. Particularly, they aim to spread knowledge about how technologies for renewables, natural gas storage, CCS, and nuclear waste disposal can be simultaneously exploited.

Our research group based its strategy on two different parallel paths: the first is to develop two university courses (within the framework of the Department of Environmental and Territory Engineering, University Tor Vergata). One course addresses renewables ("Renewable Energy Sources") that have existed from many years. The other addresses TCCO ("Transport and Sequestration of CO_2"). The courses introduce the students to both technologies and, in principle, give them the same importance. The second path includes a great effort, mostly by INGV staff, to organize international schools [1].

In particular, INGV performed the 30th and the 34th courses on these issues of the *International School of Geophysics* (Erice, Ettore Majorana Centre, http://www.ccsem.infn.it). The effort was supported by the UK and USA embassies in Rome, other research centers and industry (as a minor sponsor). The first course (in November, 2007) was titled "*CO_2 Capture and Storage: towards a UK /Italy Common Strategy within a Global Framework*", while the second (in September, 2010) was titled "*Densely populated settings: the challenge of siting geological facilities for deep geothermics, CO_2 and natural gas storage, and radioactive waste disposal*". The latter course strongly adopted (for the first time worldwide) a synergic approach to teaching about the use of the "underground space" to produce clean energy.

In our vision, by leaving the problem of "Underground Space" use (in terms of [GW h/ha/year]) and management (including liability, authorizations and monitoring) mainly to public research and to public state competent authorities, the different power-generation technologies could develop their "low-carbon revolution" without harmful competition. This should occur within the first years of accomplishment of "new" underground gas storage (i.e., CO_2). Public liability (as has been undertaken for nuclear waste disposal management by public companies such as SOGIN S.p.A) must be taken into account to allow for widespread "public awareness" and rational "public acceptance" without the development of a diffuse NUMBY syndrome ("Not Under My Back Yard").

It is imminent the 39th course of the *International School of Geophysics* (Erice, Ettore Majorana Centre, http://www.ccsem.infn.it) about geothermics, organized by our team titled: "Understanding Geological systems for geothermal energy" (September 25, October 1, 2012).

The results coming from these courses and international school are growing in time, in terms of new skills focused on these topics, highly qualified to work also in oil and gas or electric companies, as well as inside the Public Authorities staffs.

2.2. Upgrading, reviewing and merging of the European Directives with national laws for the underground. the Italian case history

We report an exemplificative case history, for Italy, where it is imperative to simplify and combine the different laws that are pertaining the underground use, including hydrocarbon exploration, geological storage (e.g., geogas or nuclear waste as well as deep geothermics) and deep geothermal exploration, into a unique law, at least for the exploration step.

This urgent regulatory framework evolution should be managed by a unique vision: "*The underground potential for clean and low-carbon power generation*".

In Italy, for example, selected as exemplificative densely populated and highly geologically risk country, the laws could be unified, are reported soon later. The merging of these laws will allow private investors to perform underground exploration with the possibility of assigning the "final destination" of a reservoir to a single underground use of the targeted geological structure. It could be possible to include feasibility studies at the regional scale, taking in consideration the surrounding multiple use of the underground, for different power-generation or industrial purposes. This is a new concept as a whole in the worldwide regulatory framework.

These above-mentioned laws under consideration in Italy are (i) the DPR (dated 09-04-1959) that addresses caves and mines – a law based on scientific research and exploration on "*non-conventional methane*" (known as *Coal Bed Methane*, CBM or as CSG = Coal Seam Gas) [19,20,31,32], that is currently obsolete; (ii) the DL 625 (dated November, 1996), an accomplishment of the European Directive 94/22 that details the possibilities for exploration and authorization of hydrocarbon production (Art. 13 defines the norms for natural gas storage, which has similar, if not identical, patterns as for geogas – in that case, why not use this law for CO_2 storage as well?) [19,20]; (iii) the DL 64/2000 on natural gas storage, which followed; (iv) Law 170 (dated 26-04-1974) that addresses the same argument as previously mentioned (this law was the first example of "*merging*" for the joint use of "underground space" for natural gas storage and depleted hydrocarbon reservoirs); (v) Law 239 (dated 2004) which did not forecast the possibility of a "change of destination" for Underground Space; (vi) the DPR 197 (dated 29-11-2009), which stated the role of UNIMIG (the Economic Development Ministry created for underground mining and use) for all the geological storage except for nuclear waste disposal (even though this could be "geological"); (vii) Law 99 (dated 23-07-2009); (viii) the DM (dated 26-04-2010) that states "*...disciplines for the explorations permits and concessions to exploit liquid and gaseous hydrocarbons on-land, in the near Italian off-shore and over the continental shelf...*"; and (ix) the accomplishment (also in Italy) of the European Directive 31/2009 on geological CO_2 storage, which still never mentioned its possible synergic use of common Underground Space with natural gas storage, geothermal binary cycles, Enhanced Geothermal Systems (EGS), geothermal "geomegmatic" probes, etc.

The actual regulatory framework in Italy also does not forecast and allow the possibility of other uses of Underground Space (after the costly exploration steps), once overcome the initial step of exploration permits application and thus it does not encourage the few private investors toward the " multiple storage" component *s* near to CO_2 Capture and Storage (CCS) Projects.

The recent EU efforts to fund EEPR and NER 300 Projects (both of which address CCS) could remain without a significant commercial exploitation of this technology in the future, as was suggested by the IEA Road Map 2009. As a consequence, the "storage" liability issues are not in the solid hands of the member states.

Moreover, we observe the recurrent use of the public geophysical and geochemical research community for the first steps (at least the exploration permits) and for communication about ongoing projects toward the general public and policy-makers: this is necessary and urgent when the public acceptance is lacking [21]. Policy-makers are very often prone to act towards options that have the maximum political consent of the mass of people and do not necessarily give their approval for the most rational scenario. They prefer to choose this option to avoid conflicts with local people towards critical type of clean-power generation, namely: safe advanced nuclear, easily-ready stored natural gas, clean coal technologies and deep geothermics, especially when the Underground Space is involved in these kind of projects in densely populated regions.

This exercise to merge "Underground Space" laws (when they are still incongruent, not synergistic and unresponsive to new scientific findings) decreases the possibility of "wars" among lobbies which use underground (sometimes inside the same power or energy enterprise), being still divided and not synergic. Lack of such merging does not allow for early strategic use of subsoil projects (i.e., for Enhanced Oil Recovery as well as Enhanced Gas Recovery) that could possibly be accompanied by deep geothermics too, in another strata of the same vertical Underground Space.

As previously mentioned, the first step of this planning is in the reworking of regulatory schemes of CO_2 geological storage (within the framework of the European Directive 31/2009): Italy finished its path for the drafting and supporting to regulatory authorities just in September, 2011 (G.U. October 4, 2011, D.L. 162/2011). Many questions have arisen recently in Italy, including whether national or regional planning will be more effective. To postpone this underground planning to a country-by-country or region-by-region strategy (as must be done for potable groundwater reservoirs) is becoming a luxury.

All of the mentioned technologies must be implemented together regionally in a planned and safe manner, with equal "space" and "incentives" for both inland and underground implementation. According to the EU Commission Set-Plan-Final Document COM (2007) 723, a focus on the requirements of the entire system, including efficiency, safety and public acceptance to prove the viability of zero-emission fossil fuel power plants, at an industrial scale, is recommended.

2.3. GIS tools

During our cataloging of the best sites for natural gas storage, CO_2 storage, deep geothermics and possibly for nuclear waste disposal (despite here the criticalities are higher), characteristic patterns of GIS layers that are related to inland infrastructure and environmental objects are also necessary. Such layers include population activities, soil use for agriculture, manufacturing industries and military installations among others. If the value of the "Underground Space" below each sector is well known, synergistic development of such a catalog could help to avoid inland "building speculation". This is true mostly at local levels, but would also be true for regional and national scale if planned sufficiently early. An Italian GIS case history is reported (Fig. 1).

We began our work with the Lazio and Campania Regions in Italy for the following reasons: (i) they are among the most densely populated regions (and therefore there is maximum political interest in solving the Underground Space merging question) and (ii) they have been mentioned critically in the past regarding the use of Underground Space, such as "*near-surface*" nuclear waste disposal, deep geothermics, CO_2 storage [6–10,19,20] and natural gas storage. As a whole, they are ideal training regions for this synergic cataloging activity that is promoted in Italy by INGV.

The GIS layers were developed to include IAEA prerequisites (i.e., IAEA, Safety Series No. 111-G-3.1) to address site-selection for CO_2 storage, gas storage, deep geothermics as well nuclear waste disposal. The latter represent the most critical and "exclusive" criteria in comparison with the others (i.e., for CO_2 storage see the European Directive 31/2009 which in Italy was published as D.L. 162/2011).

Every layer was added into a dedicated GIS starting from data coming from different INGV data set as well as Economic Development Ministry data set [19,20]; layers represent not only territorial information but also exclusion layers for any kind of underground space use. Considering the recent Italian choice to build this kind of national storage facility, this product could be useful to SOGIN (the agency in Italy focused on nuclear waste repository with Law 31 dated on 15-02-2010) to identify the LARW (Low-Activity

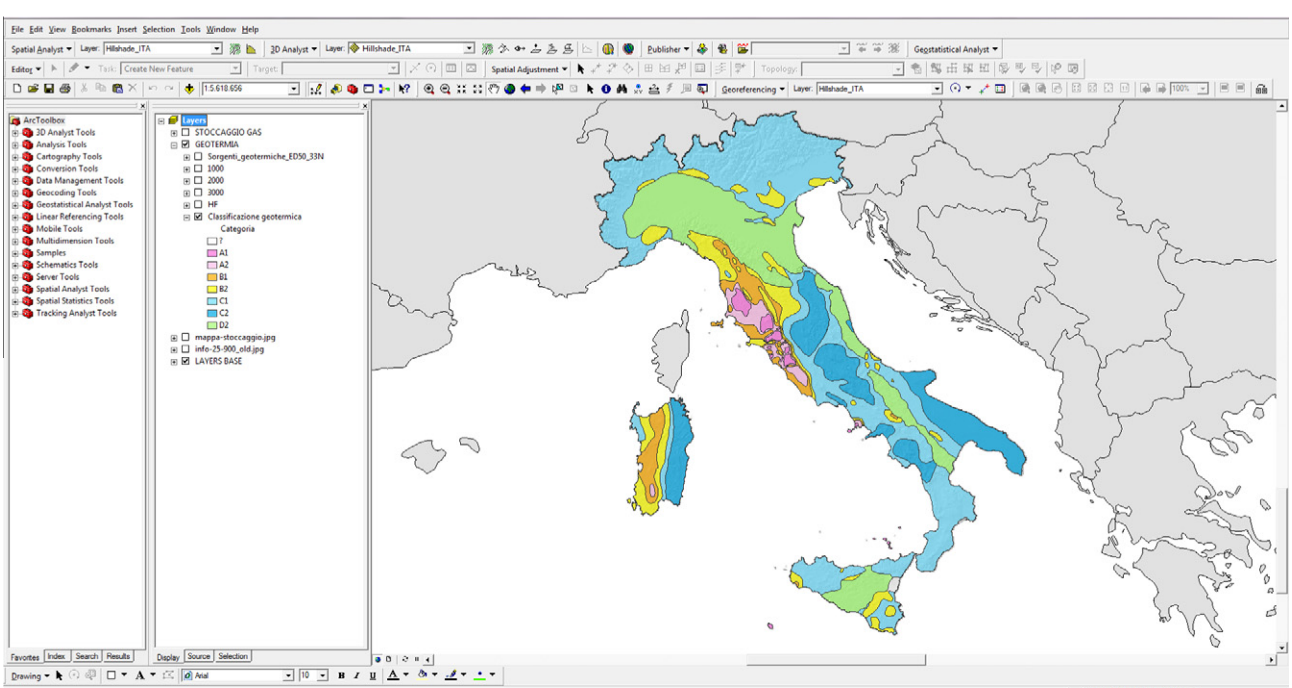


Fig. 1. Ongoing upgraded GIS i.e., strata "Geothermal Ranking of Italy" (software ArcGIS, Version 9.0). The overall discussion is il the text.

Radioactive Waste) "*near-surface*" disposal sites. In particular we built up and used the data reported in Appendix A.

Maps of the underground potentiality (in terms of energy) were compiled, and could be requested on a region-by-region basis (considering the current regional energetic plans and urgency for some regions). Currently, the most complete data sets are compiled for the Lazio and Campania Regions.

2.4. Geothermal data set

Geothermal Energy is a renewable, clean, sustainable and low-carbon energy source that can be used indirectly for electric power generation and directly for numerous applications such as space and district heating and cooling, water heating aquaculture, horticulture and industrial processes. In Europe Italy, Iceland, Portugal, Austria, Germany and France produce electricity from high and medium enthalpy deep geothermal systems (1471 MW) [1,33]. In several European countries, geothermal energy is also used on small scales (mainly for a heating supply and for heat/chill storage using low-enthalpy "liquid fluids"). Development worldwide scenarios foresee about 18.5 GW of installed geothermal electric capacity by 2015 whereas the European scenario foresee about 2000 MW [1,33]. In Italy the main ancient data set are_ AGIP Technical Report aged 1987, ENEL "Inventario Risorse Geotermiche Nazionali, 1987".

An increase in geothermal resource use could notably contribute to both decreases in CO_2 emissions and to the resolution of the global energy crisis. The development of research on renewable energy (especially if associated with CCS) could play a crucial role considering Kyoto Protocol aims to reduce greenhouse gas emissions.

In Italy, power generation from geothermal energy is about 5400 [GW h/year]. It comes exclusively from Tuscany, where the main geothermal fields are Larderello–Travale and Mt. Amiata, while other hot regions, as Campania [47], are not producing heat and energy.

On the other hand, direct applications of geothermal low-enthalpy resources are widely used for home heating/cooling in Northern Italy (especially in Friuli Venezia Giulia, Emilia Romagna, Veneto and Trentino Alto Adige). Although there is huge potential for their use along some fault systems, they are not widely used Central and Southern Italy.

Fluid geochemistry applied to seismotectonics could give some hints on geothermal potential along faults [11–13,15,16,24–28]. Recently, there are some projects were launched within our group for the Latium Region and others were conceived for low-enthalpy research in cooperation with the University of Roma 3 (INGV unpublished, confidential data, after [46].

In Italy, research on renewable energy sources has been growing recently. This is especially true for medium-enthalpy geothermics because the Italian territory has a huge potential for such energy that is completely unexploited. This limited application is often due to inadequate knowledge of the territory and it is sometimes due to difficulties in obtaining required deep-strata information.

In this framework, the creation of a geo-database (Fig. 1) that includes all of the geothermal depths (from the surface to 5000 m) would be extremely helpful. In our dedicated GIS, useful information about geothermal exploration and exploitation has been included (especially for the Latium and Campania Regions; Figs. 2–5). The inserted information regards the following:

- temperature at 500 m depth;
- temperature at 1000 m depth;
- temperature at 2000 m depth;
- temperature at 3000 m depth;
- heat flow;
- geothermal ranking;
- the top of the carbonate reservoir;
- the temperature at the top of the carbonate reservoir;
- land use;
- demographic density.

The creation of a dedicated geo-database has been a necessary initial step for the research of potential storage sites in Italy and for attracting private operators for geothermal power exploitation.

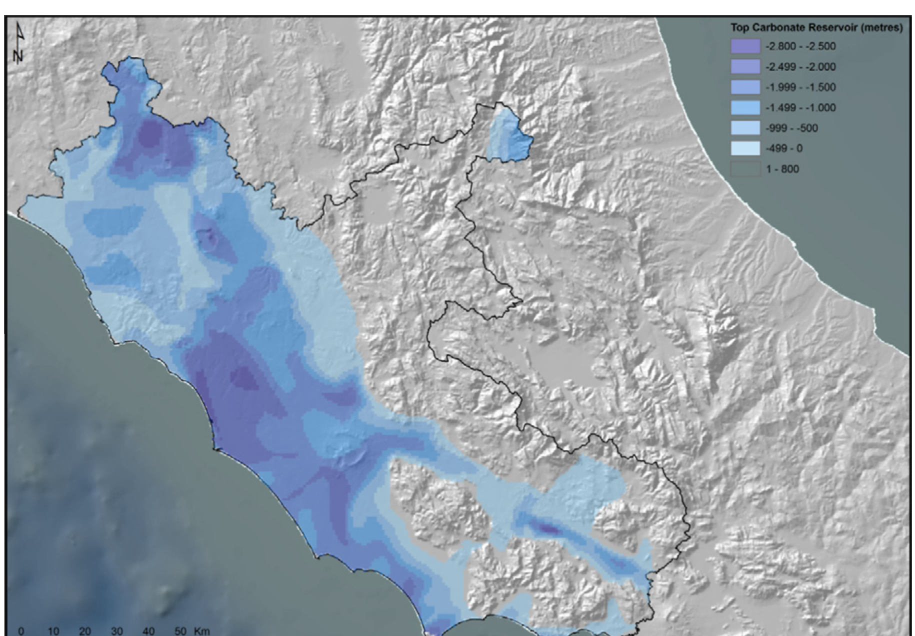


Fig. 2. A peculiar GIS strata, which is very useful to discover the depth to be reached, during drillings. The top of the carbonate reservoir for the Latium Region (Central Italy) from D-GIS. The deepest top is dark-blue in color. The knowledge of the top reservoir depth is very useful both for identifying suitable areas for the discussed technologies (i.e. deep geothermics) and for planning the potential and costs for each technology in that Region.

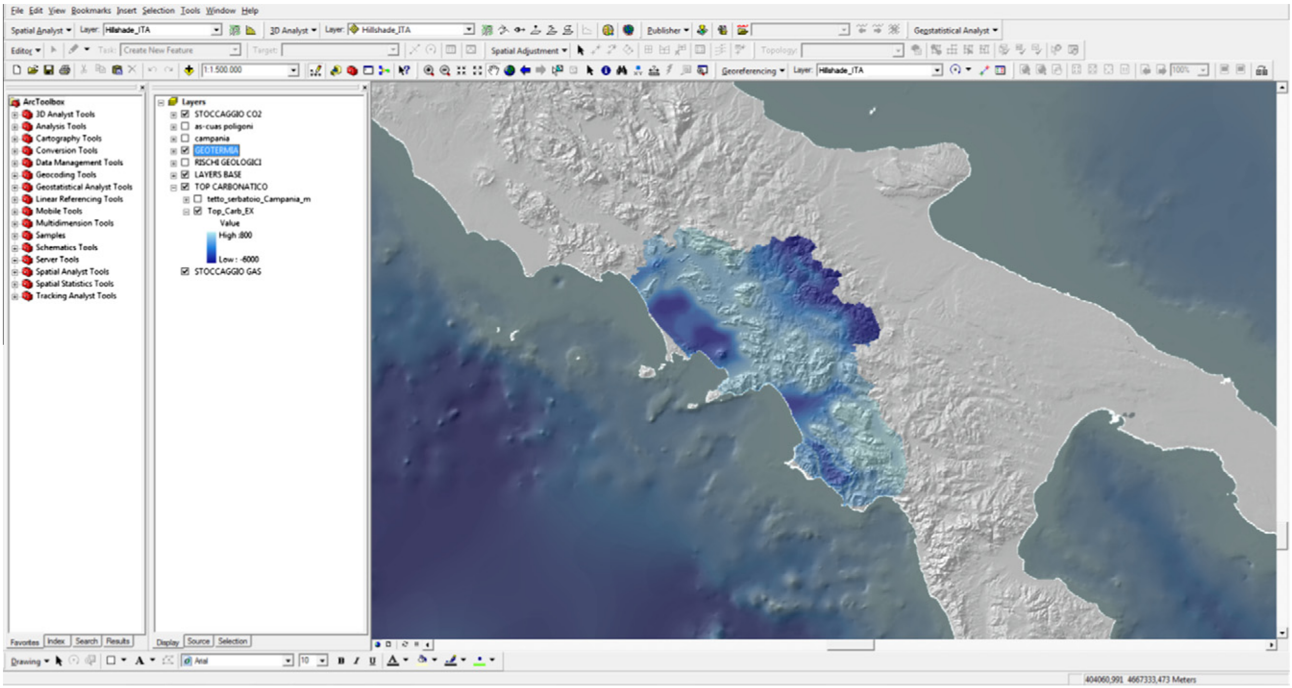


Fig. 3. A peculiar GIS strata, which is very useful to discover the depth to be reached, during drillings. The top of the carbonate reservoir for the Campania Region (Central Italy) from D-GIS. The deepest top is dark-blue in color. The knowledge of the top reservoir depth is very useful both for identifying suitable areas for the discussed technologies (i.e. deep geothermics) and for planning the potential and costs for each technology in that Region.

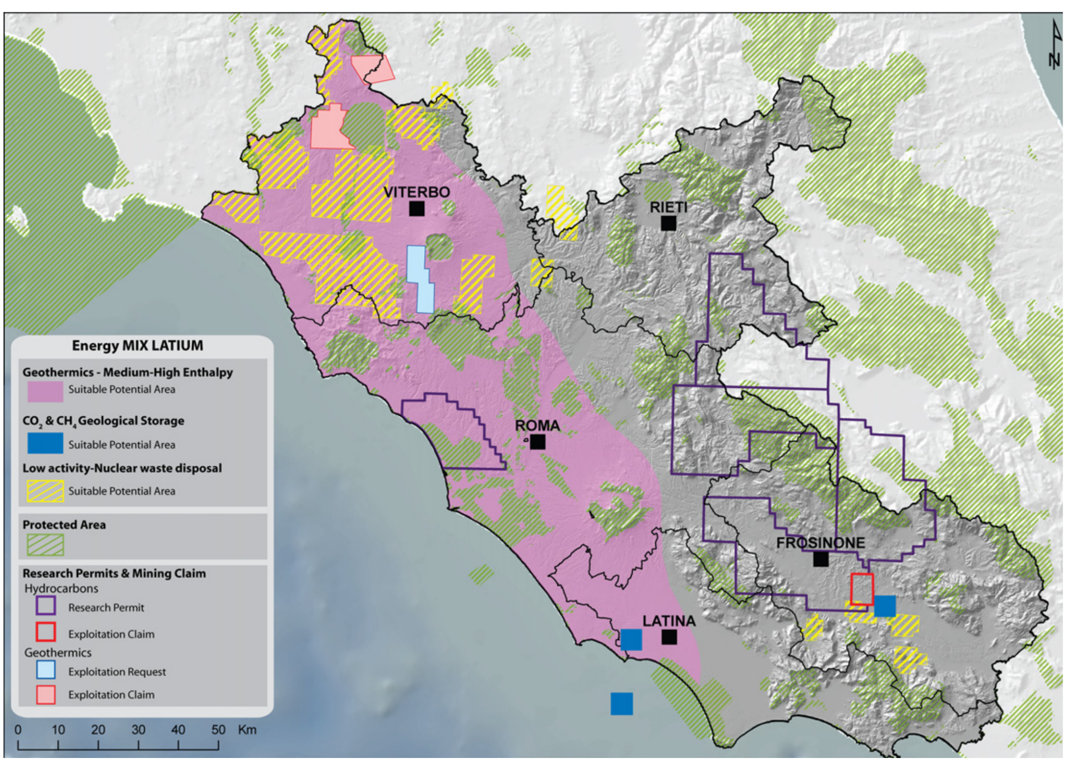


Fig. 4. Overall underground potential for the Lazio Region (Central Italy), as regards: (i) geothermics, geological storage sound structures (not yet quantified specifically as capacity). Nuclear Waste disposal areas from the 2001 provisory SOGIN map. Obviously the future new maps will be reworked on the basis of the new findings from science. For the discussion, see the text in this case.

This can be a useful tool for identifying potential areas where the basic prerequisites for geological storage and geothermics are present and for considering the distance and presence of main geological hazards (e.g., seismicity and degassing). The information is very strategic for local authorities (e.g., municipalities, provinces, and regions) and for multi-technological operators, which could decide how to address the initial exploration phase.

The dedicated GIS geo-database has been compiled including the following inserted layers (improved after [19,20]): (i) caprock and deep aquifer information for the Italian territory; (ii) the

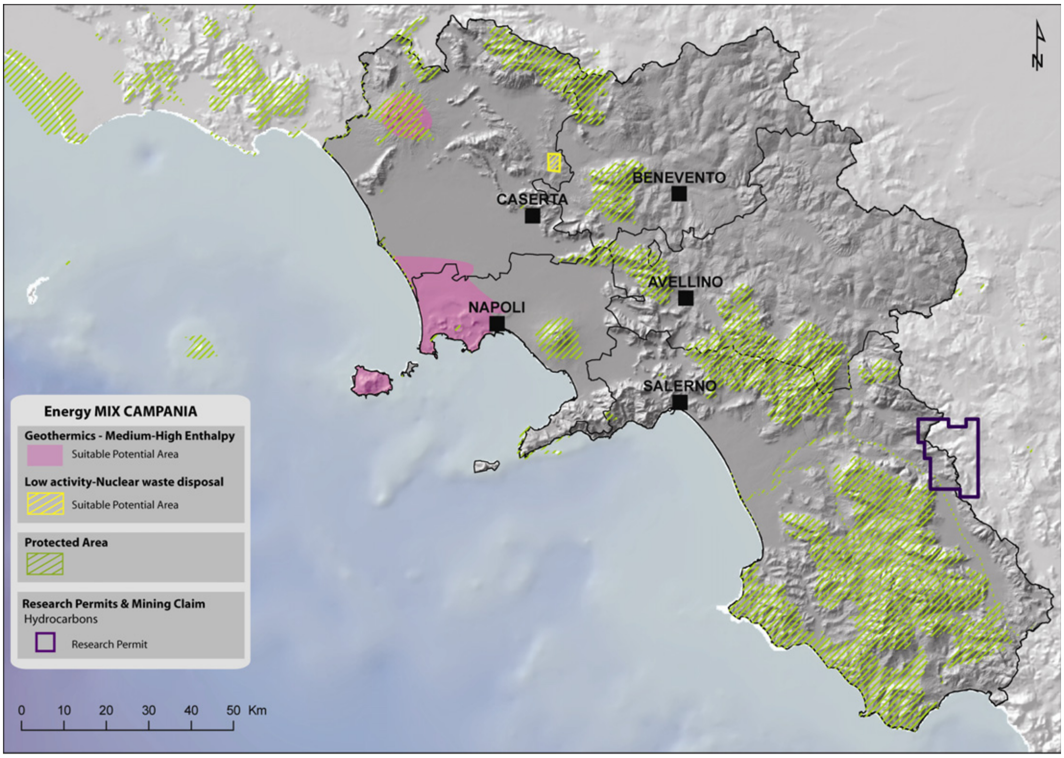


Fig. 5. Overall underground potential for the Campania Region (Central Italy), see the text.

locations of geological risk factors (i.e., seismicity, degassing structures, landslides); (iii) the previous distribution of heat flow and geothermal anomalies; (iv) anthropogenic emission sources; and (v) infrastructure items such as densely populated areas, roads, natural parks, and land use.

During 2009–2010, this work led INGV to the definition of areas that could contain geological storage structures targets of different storages. The work was a prerequisite for some feasibility studies that INGV began with oil companies and power plant generation companies and that are still ongoing, mostly taking in consideration saline aquifers in fractured carbonate rocks [9,10].

This work represents only a first step for research aimed at the local and detailed identification of Italian potential injection sites: as a whole, 2–3 years of work are necessary for each geological structure to be detailed studied for a geological storage destination, following ANNEX 1 of the European Directive 31/2009. This tool is therefore available at INGV for the operators, stake-holders and oil companies.

Owing to the exhaustible nature of geothermal resources, sustainable heat mining is of the utmost importance for designing and implementing relevant "site-specific" resources and for adding value and cost to single out structures. Sound and effective reservoir engineering studies allow developers to optimize energy extraction from a specific geothermal field and to extend its commercial life. This lifespan could be very different among geological structures in the same region. This is one peculiar characteristic of Underground Space and is also true for geothermal exploitation, different than geogas geological storage.

A table sums up different characteristics of the mentioned use of underground to produce "low carbon" energy (Table 1). This factor demands the strong input of the public authorities who can make use of this tool in the decision phase to address State liability issues.

For the GIS implementation, it is strongly necessary to add the polygons corresponding to the projections of the deep storage/reservoirs at depth: The first geological tool for "site specific" applications to create polygons is 3D-reservoir engineering, which is able to visualize the entire geological structure to be filled by geogas, and how this geogas creates a plume during the injection.

Currently, reservoir engineering modelling is required to construct a realistic conceptual model of the field including subsurface temperature and pressure distributions (in both vertical and horizontal planes), the distribution of chemicals and gases, field boundaries, reservoir storage and transmissivity, and the flow of fluids both within the reservoir and across the boundaries. All of these activities are highly "site specific" and are therefore associated with huge States liabilities; thus State involvement and public research involvement is necessary from the beginning phase of any project.

To realize these strategies is beyond the scope of available mature technologies and requires the development of new cost-effective technologies for (i) significantly enhancing production from

Table 1
For each underground use a matrix of different variables should be created and managed for each "smart region".

Underground USE	Depth (m)	Geothermal gradient (°C/km)	Presence of caprock	Presence of reservoir
CO_2 geological storage	⩽3000	<40 (T < 120 °C)	×	×
CH_4 geological storage	⩽3000	<40	×	×
Geothermic	⩽5000	>40 (T > 90 °C)	×	×
Nuclear	⩾500	<40	×	–

already identified and utilized resources, (ii) large-scale exploration of new untapped and deep-seated (up to 6 km) hydrothermal systems, and (iii) accessing new extreme "high-potential" resources such as supercritical fluids and geo-magmatic systems [1].

Geomagmatic energy could represent a new technological frontier for power generation that has been entirely developed by Power Tube Inc.® [1]. In Italy, we have not yet exploited this technology, which does not seem to require the presence of fluids at depth. It is an integrated closed-loop system that is totally based on the direct use of natural underground heat (with a temperature range between 105 and 210 °C to be reached within 1.500 m), that makes no use of water in any phase of the process. With its single-hole system, in which each module uses only about 100 square meters surface area, it makes absolutely no environmental footprint, and it seems to fit perfectly in densely populated urbanized areas as well as in natural protected areas with high attractiveness for tourism. Geomagmatic Energy technologies are currently designed in three different-sized models: 1 MW, 5 MW and possibly, in special conditions, 10 MW (see after the calculation results for its Energy Density Potential in Land (EPDL). This kind of installed electrical power device provides continued base-load capacity during the year. Moreover, because Geomagmatic technology does not use, in theory, any water or any other fractured-rock systems, it could also be a valuable answer for securing the compatibility of geological sites across several industries (power generation and CCS in particular). Thus, by using integrated strategies to cut carbon emissions, these technologies could create very valuable synergies in the fight against climate change.

2.5. 3D modeling data set

The underground potential ranking, both for storage and for geothermics, makes use of the powerful 3D-modeling tools. INGV is working jointly with the CNR group on this issue [9,10]. In the last decades, the increasing availability of digital geophysical and geological datasets has been coupled with the development of powerful 3D-modeling applications. These tools represent a challenge for building reliable and consistent 3D subsurface geological models, in which data and knowledge are fully combined. 3D models may also contribute to overcoming several of the existing limitations that are inherent in the traditional 2D methods of analysis and representation (e.g., maps and seismic reflection/geological cross sections). Furthermore, when reconstructing 3D models, geoscientists toned up to check for data consistency and to understand the spatial relationships among structural and stratigraphic features, indispensable for a regional scale planning. Building 3D subsurface models requires the integration of multi-scale and multi-source geo-referenced data, generally including the following: surface data including digital elevation models (see Figs. 2–5), geological maps (e.g., faults, geological boundaries, and dip data), imagery (e.g., satellite images and aerial photos); subsurface data (such as borehole well-logs and core measurements) and geophysical information (such as 2D/3D seismic-reflection data, and gravimetric and magneto-telluric surveys). These different datasets may be integrated into a single 3D reliable environment where the final interpretation and modelling are carried out.

As a first step, the modelling procedure often involves the reconstruction of fault systems detailed as fracture nets (and taking the advantage of the previous INGV cataloging such as the DISS Active faults catalog). In this way, the modelled volume is subdivided into blocks by fault surfaces. Geological surfaces are then interpolated separately within each block [43].

In complex geological settings (e.g., thrust belts or complex fault segmentation), a validation of the structural interpretation may be appropriate. 2D and 3D software tools for structural restoration and analyses can help to build more robust structural

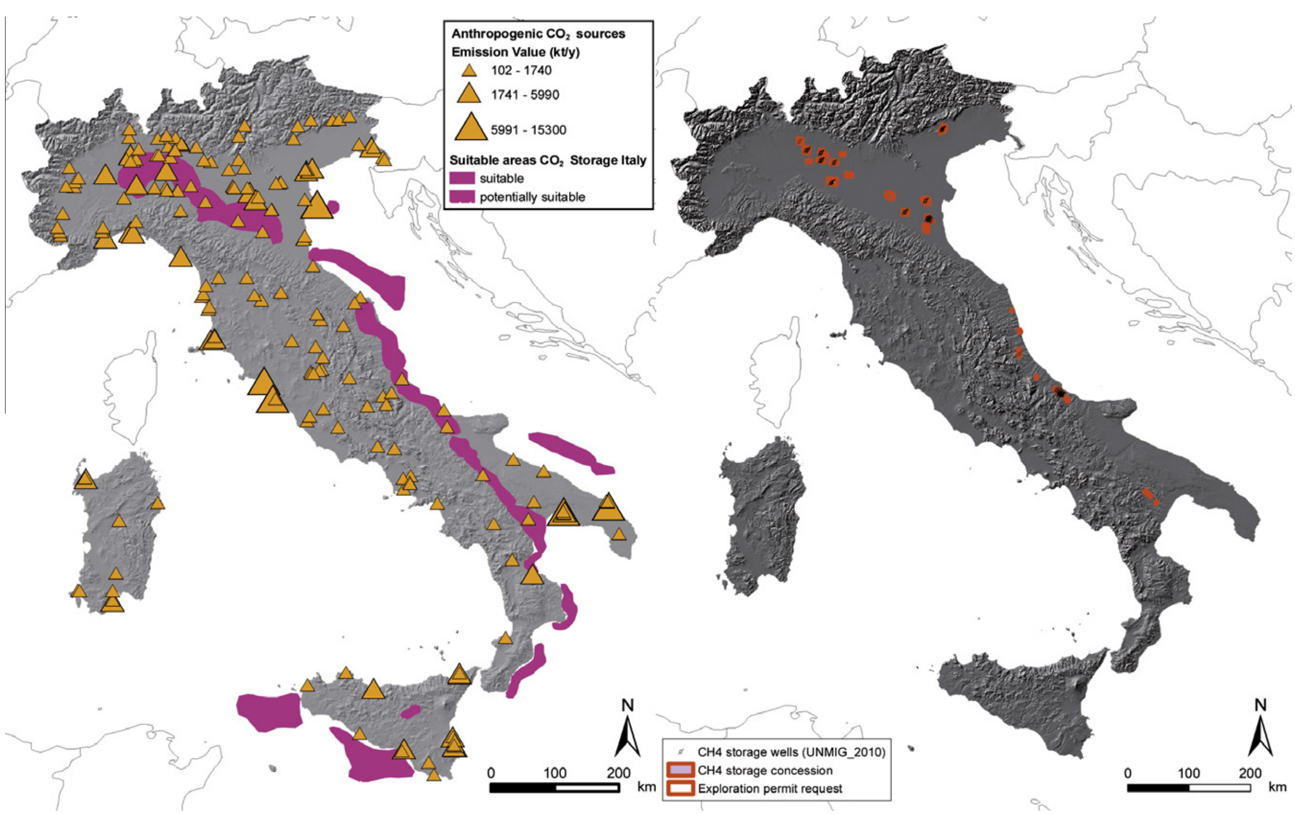


Fig. 6. (a) Distribution of promising areas within the Italian territory for geological CO_2 storage, from Refs. [19,20] and (b) Italian distribution of CH_4 storage wells and concessions (see for example the Nomisma Energia Report 18-02-2008).

models. When seismic reflection data are used, the model is usually built in the time domain. To depth-convert a model reconstructed in the time domain, a 3D subsurface-velocity model needs to be elaborated by interpolating the available information about the seismic velocity of the geological formation (usually derived from well measurements such as sonic logs, check-shot surveys and vertical seismic profiles).

The resulting model can be used to populate the space with rock petrophysical properties such as porosity, permeability, temperature, and heat conductivity within the 3D volume reservoir. Reliable 3D geological models are usually required as input to other tools (such as reservoir simulators) that are able to predict the behavior of the rocks under various scenarios (e.g., fluid flow, geomechanical behavior and geochemical reactions).

These techniques, which were originally developed by the oil industry, are now applied in a wide variety of contexts including CO_2 and CH_4 geological storage at national scale (see Fig. 6), geothermics, and radioactive waste disposal.

Italian modelling expertise for natural gas storage was born before any other experience in Europe (the first natural gas storage born during the '30 in USA!) with the needs associated with the production and distribution of natural gas. The first field was Cortemaggiore, which is now used for CO_2 storage (2012–2013). The national market developed under conditions of a monopoly that resulted in a single type of storage in depleted fields. Gas reservoirs are easily available and are hosted mainly in terrigenous formations with porosities of between 10% and 30% and extremely variable permeability (between 1 and 1000 mD). These data are indispensable for the reservoir modelling (mass-flow or reactive mass-flow modelling) [5–8,18] that follows the 3D-modelling.

From an engineering point of view, it is important to understand the real possibilities for the use of a storage site and to recognize its optimal use [9,10,17]. Firstly, the capacity of a site for CO_2 and CH_4 storage must be studied.

This capacity concerns the two main systems that are available in nature to host fluids in rocks, namely, pores and fractures [9,10]. Depending on the equilibrium between them, the reference model could be classified as single or double porosity for both CO_2 and CH_4 storage. In any case, the concepts of capacity, containment and injectivity or deliverability should also be balanced. Permeability is a key issue for characterizing the media for both CO_2 and CH_4 storage.

However, geological CO_2 storage arisen for climatic purposes but it is very critical as regards the huge quantity of CO_2 to be stored underground (>1 million tons of CO_2 can be injected into a unique geologic structure in a few years – this is one of order of magnitude lower than the typical Enhanced Oil Recovery amount), and this is not comparable with the natural gas storage sites. In both cases of CO_2 and CH_4 storage there is a growing need, also for stakeholders and policy-makers and citizens to study fault systems, induced or triggered seismicity, subsidence, leakage during mass-transport processes, as well as the buffer capacity of caprock. At a pore scale, these aspects influence behavior at a reservoir scale [41].

The overpressure, for both CO_2 and CH_4 storage, obtained by injecting gas into an underground structure depends on how fast the gas is injected and on the total volume injected. Higher pressures arise with more rapid gas injection.

It is very important to understand that depleted reservoirs are very different from aquifers with regard to gas injection [9,10]. If the aquifer activity is low, then gas injection is very easy and the depleted reservoir can be refilled without any problem. When aquifer activity is high, the pressure in the reservoir tends to increase rapidly and injection can be quite difficult. In this case, the injection into aquifers is not very different from injection into depleted reservoirs [9,10]. Risk studies have demonstrated that failures in gas storage facilities worldwide are extremely rare (failure rate > 10^{-5}).

Competition between existing or planned underground activities and the new welcome CO_2 storage might not necessarily be an imperative. There might even be synergies or options for coexistence between CO_2 and natural gas storage, as for case histories of use of CO_2 as cusheon gas. These should be researched and further assessed with regard to legal, safety, and environmental aspects.

2.6. Energy Density Potential in Land (EDPL), the case of geothermics in comparison with the other renewables

Landscape and territory, are subjected to conflicts arising from their multiple uses, in terms of Energy Density Potential in Land (EDPL onward).

Not only hydroelectric and geothermal exploitation, but also solar and wind applications, reduce the possibility of an improved energy management of land, the use of which, in terms of EDPL is tending to a functional saturation. In addition, the concept of "territory" should be extended to the dual meaning of upper-surface and subsurface, namely the underground, as described in the previous paragraphs. Therefore the EDPL concept includes the underground potential to produce energy. The surface that bounds this duality, together with its projection, is therefore of critical importance.

This latter aspect is strategic in the possibility of defining technical and social criteria of either inclusion and exclusion, thus allowing to decide which activities can be accepted or excluded on the basis of the belonging to territorial domains both upper-surface and subsurface, for which the "surface" dimension must be integrated by the "underground" one, in the first case the altitude (e.g. the height of chimneys, of wind turbine, points of entry into the atmosphere) and in the second case the depth (e.g. the development of geothermal reservoirs and storage formations).

The method used in this paper to calculate the energetic potential in land, namely the EDPL implies that energy production can be considered proportional to the area engaged by the plants, so that the replacement of fossil fuel power plants by renewables need huge territorial extensions, of the order of thousands of km^2.

As a matter of fact, with the photovoltaic panels it is possible to obtain values of EDPL from 0.5 up to a maximum of 1 [GW h/ha/year], where ha is hectares of land engaged, against a yield from 5 to 10 times greater with the hydroelectric source [44].

From that territorial point of view, the use of wind power [45] falls below the solar one in terms of potential productivity, namely EDPL, with values from 0.1 to 0.17 [GW h/ha/year] (without considering the visual impact; but we have to say also that his commitment of land does not exclude other uses, such as livestock uses), as well as traditional geothermal does, with values of about 0.11 [GW h/ha/year], as shown in Fig. 7.

Referring to medium–high enthalpy deep geothermal (up to 2000–3000 m depth), it is possible to obtain EDPL yields from 0.1 to 1 [GW h/ha/year].

On the other hand, considering low-medium enthalpy geothermal (within a depth of 2000 m), it is possible to obtain EDPL yields from 0.05 to 0.19 [GW h/ha/year].

For the sake of completeness, it needs to be considered that geomagmatic technology, among the geothermal ones (Table 2), which is ascribed (Power Tube Inc.™) is ascribed to reach values of EDPL of about 800 [GW h/ha/year]: if confirmed it would be higher by a factor of a thousand than the other technologies. A strong confidentiality is around this technology, despite some information was published [1, p. 45].

However, with regards to Lazio Region (Fig. 8) we considered as a starting point data relating to the so-called non-constrained

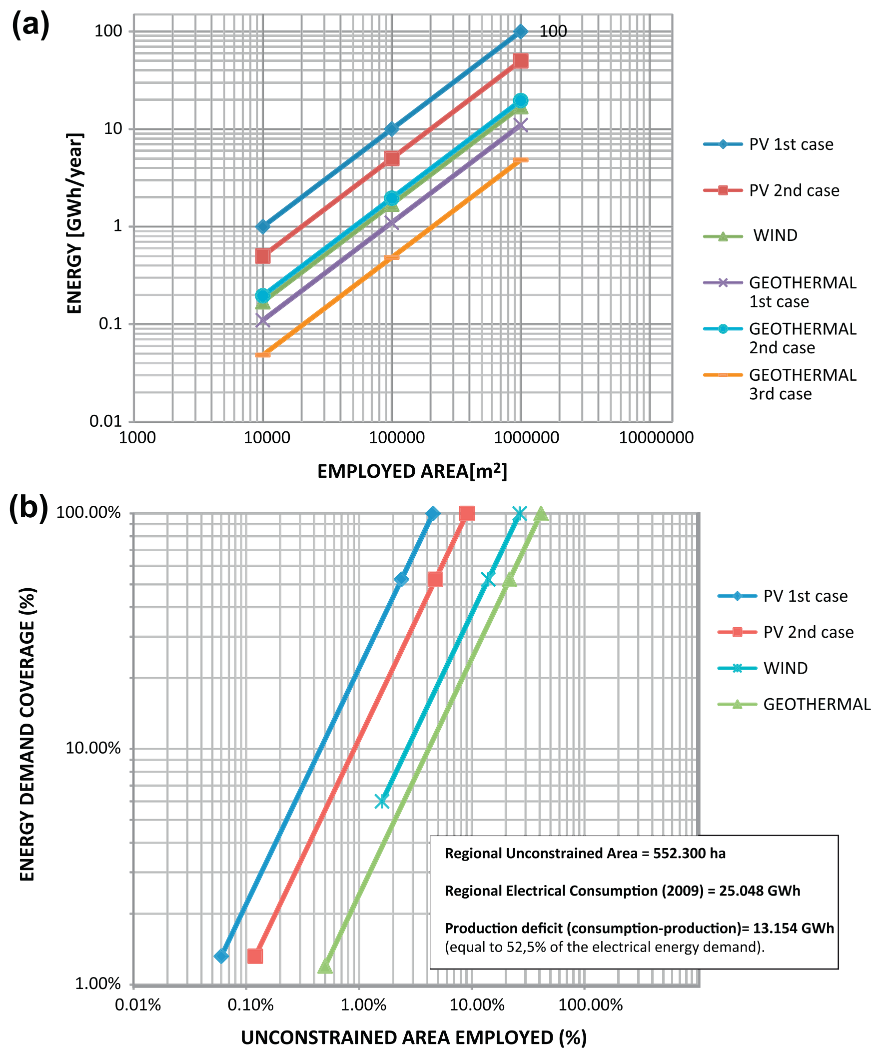


Fig. 7. (a) Specific gross energy production per year in the Lazio Region. (b) Percentage of energy and demand covered in the Lazio Region as a function of the percentage of unconstrained area occupied by the different technologies considered.

areas, which, according to the PTPR 2007, represent about 33% of the total regional surface. Since this amounts to 17,203 km^2 (1,720,300 ha) unconstrained areas amount to 552,300 ha.

We also considered that, for each technology there are eligibility criteria to enter inside the EDPL in terms of [GW h/ha/year] and both territorial and technological constraints to be observed and that restrict their application, whereby the suitable areas for each of them are automatically much lower than the availability of unconstrained areas.

Fig. 7 shows the percentage of the demand meet in the Lazio Region as a function of the percentage of unconstrained territory occupied by each technology. The graph was obtained by considering the following statement: although geothermal energy is placed below the other technologies in terms of EDPL [GW h/ha/year], it must be stressed its importance in relation to the high geothermal potential of the Lazio Region (as shown in the following map obtained by D-GIS processing, after data collection [46]), particularly in the northern area of Lazio if referring to the electricity production. This takes on greater significance in relation to the increased development that it can be assumed for this technology compared to the other, as in the current state it is totally absent.

For the Campania Region we are mainly referring to the paper [47] and other our available data, which have been only grossly evaluated, but not like the Lazio Region.

2.7. Diffuse degassing structures data set

For all mentioned geological storage type and for geothermics, methods of near-surface gas geochemistry can provide critical information with regard to potential sites and migration pathways (as faults). Throughout the Diffuse Degassing Structures (DDSs) as a whole, fracture systems can create clear geochemical anomalies marked by higher values of ^{222}Rn, He, H_2, CO_2, CH_4 in both soil–gas concentrations and in CH_4 and CO_2 flux measurements. The DDS are located mainly along fault and fracture zones. They are very important for discriminating potential geothermal sites and for locating sound geological storage sites that optimize their reciprocal positions. Recently, this type of geochemical surveys method was also applied to geological CO_2 storage [34,35].

Many papers have been published the recent past have shown relationships between fluid discharge and seismotectonics: these papers are now very helpful to be reworked in search of new assessments of geological storage and geothermal risk and potential [12,13,15,24–28,36]. At the same time, nuclear waste disposal makes use of the important old concepts of “geological barriers”, “multi-barriers”, and “geological analogs”.

These concepts are the benchmarks of “deep” geological nuclear waste disposal, nowadays completely under-evaluated worldwide, without apparent motivations [36–40].

Table 2
Schematic view of all the geothermal technologies used to produce energy and direct uses (heat).

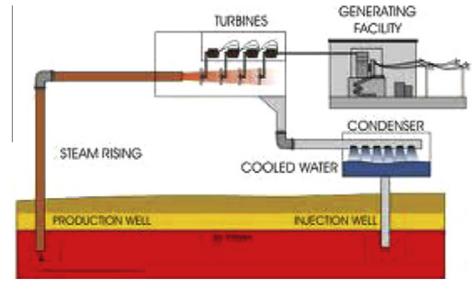
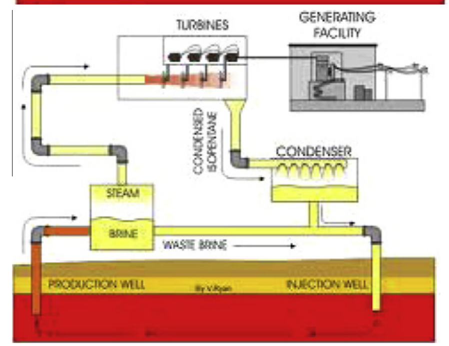
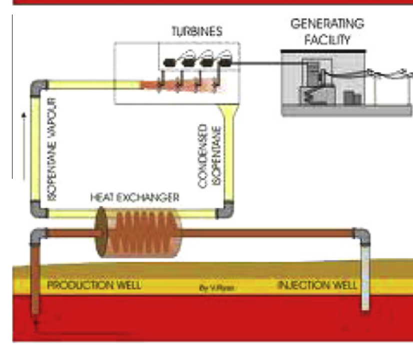
Plant typology	Enthalpy	Fluids injection (X)	Fluids extraction (X)	Depth (m)	Temperatures (°C)	Requirement	Environmental impact	Country	Scheme	Company & Research Institute
Dry Steam	H	X	X	<3000	150–380	Availability of steam	Bad smell – minimum Noise – minimum Pollution – minimum Seismicity - minimum	Italy, Indonesia, Japan, New Zealand, USA		*Company*: • USA: Calpine, Chevron, Terra Gen, Cal Energy Generation, Northern California Power Agency, Nevada Geothermal Power, Constellation Energy/Ormat, Pacific Corporation • Philippines: Energy Development Corporation • Mexico: Comisiòn Federal De Electricidad • Italy: Enel Green Power • Israel: ORMAT • New Zealand: Contact Energy, Tuaropaki Power Co, Ngati Tuwharetoa Geothermal Assets • Iceland: Orkuveita Reykjavikur, Hitaveita Sudurnesja, Landsvirkjun • Indonesia: Star Energy Ltd • El Salvador: LaGeo/Enel Green Power • Japan: Kyushu Electric Power, Nittetsu Kagoshima Geothermal • Costa Rica: Istituto costarricencse de Electricidad • Kenya: KenGeo • Guatemala: Istituto National de Electrificatiòn • Russia: SC Geoterm • Papua New Guinea: Lihir Gold Ltd mine • Turkey: GURMAT • Portugal: Electricidade dos Acores • China: Electric Power Tibet *Research institute*: • Europe: CNR, INGV, GFZ, ETH, CHYN, BRGM, Iceland GeoSurvey, Geothermie Soultz, KIT, GPC, TNO, Centre for renewable energy sources (Grecia), Centre for research and technology Hellas,
Flash steam	H	X	X	<3000	150–380	Availability of fluids	Bad smell – minimum Noise – minimum Pollution – minimum Seismicity - minimum	China, Costa Rica, El Salvador, France, Iceland, Indonesia, Italy, Japan, Kenya, Mexico, New Zealand, Nicaragua, Papua NewGuinea, Philippines, Russia, Thailand, Turkey, USA		
Binary Cycle	M	X	X	<3000	90–180	Availability of fluids	Noise – minimum	Austria, Australia, Costa Rica, El Salvador, Ethiopia, France, Germany, Guatemala, Iceland, Japan, Kenya, Mexico, New Zealand, Nicaragua, Philippines, Portugal, Turkey, USA		

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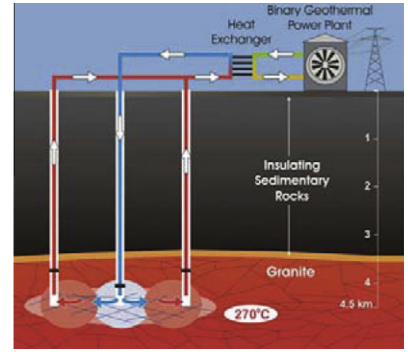
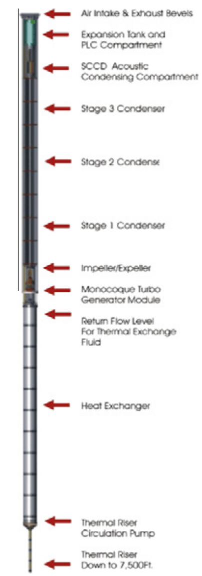
Table 2 (*continued*)

Plant typology	Enthalpy	Fluids injection (X)	Fluids extraction (X)	Depth (m)	Temperatures (°C)	Requirement	Environmental impact	Country	Scheme	Company & Research Institute
EGS	M–H	X	X	<7000	200–300	High deep temperatures and permeability	Seismicity – minimum/ medium	USA, Australia, Germany, Japan, United Kingdom, France		The Institute for geothermal research of the daghestan scientific centre of russian academy of sciences • USA: Geo-Heat Center - Oregon Institute of Technology • Geothermal Institute • New Zealand: University of Auckland, Wairakei Research Centre • Mexico: Instituto de Investigaciones Eléctricas, Gerencia de Geotermia • Costa Rica: Instituto Costarricense de Electricidad e Centro de Servicio Recursos Geotérmicos • Japan: Kyushu University • Philippines : Energy Center • Australia: Primary Industries and Resources SA
Thermal Riser (Power Tube)	M–H	–	–	<2000	$120 \leqslant T \leqslant 210$	High thermal conductivity of the rocks. Thickness of the rock 300–600 m	?	–		

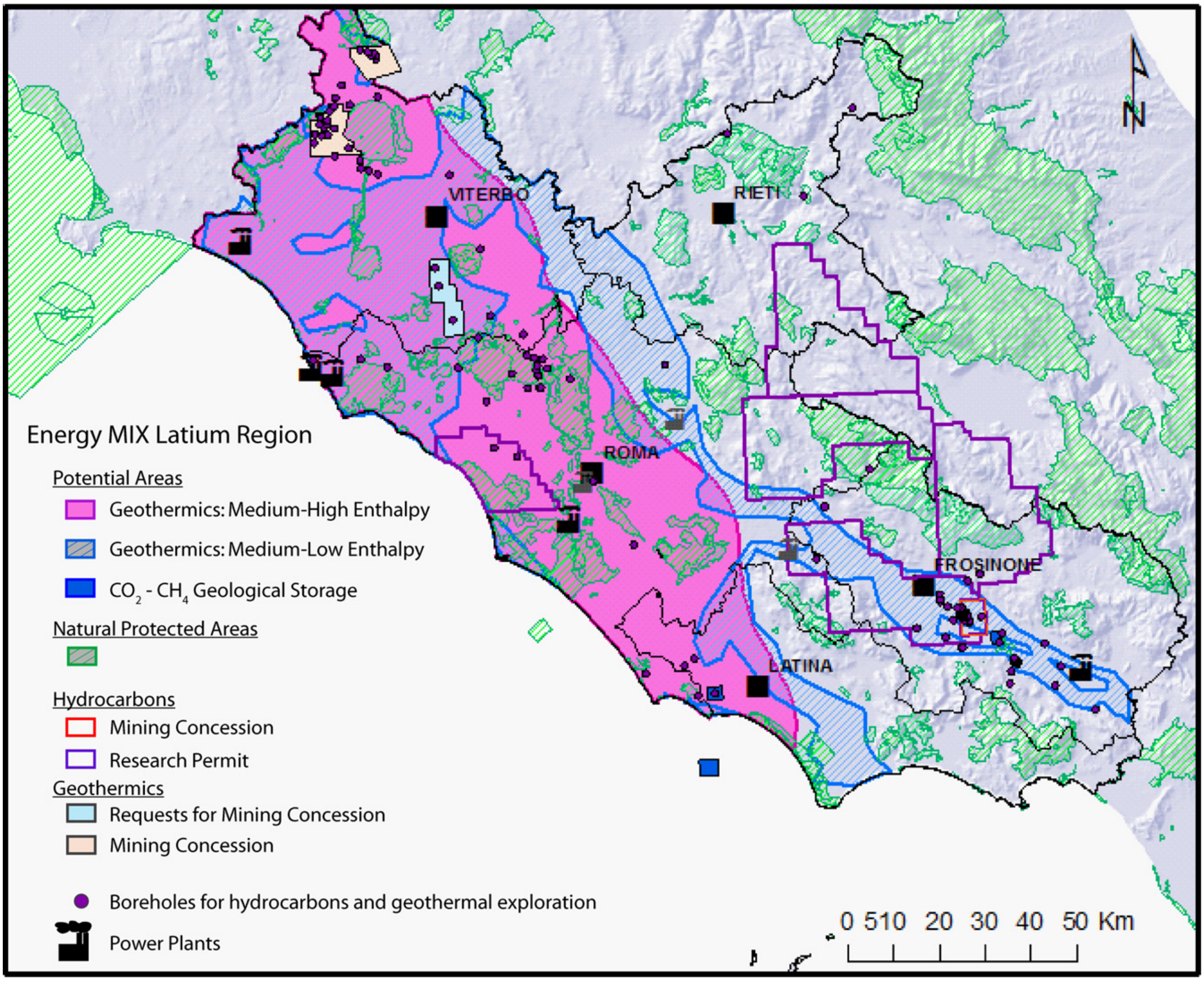


Fig. 8. Map of the future perspectives of the new concept of energy mix for the Lazio Region (Central Italy): towards the development of the Regional Energy Plan.

This knowledge was initially mainly present in Italy, where an historical scientific school arisen (see in [1]) and later was spread elsewhere. This information allows for estimation of the soil degassing potential of an area and of the natural gas leakage potential [12,14,16]. The importance of this tool has increased after the Weyburn advice of a possible CO_2-leakage episode in January, 2011 (after [35], PTRC Reports, New York Times 22/01/2011; Scientific American 10/01/2011). Indeed, complex studies that allow for the definition and delimitation of possible gas escape routes in case of the normal processes of "leakage" (gas leakage from underground) and "seepage" (leakage of underground gas into the lower atmosphere) of deep-origin geogas are crucial to obtain a realistic vision with regard to natural degassing structures (e.g., CO_2, CH_4, and ^{222}Rn).

In Germany, for both CO_2 and CH_4 storage, the lack of public awareness of the concept of "CO_2 or CH_4 natural leakage" is creating a delay in CCS commercial deployment (see Herald Tribune, January 17, 2012). This is despite the recent German government outline of the path to achieve greenhouse gas emissions–reduction goals that included CO_2 Capture and Storage (CCS). Two issues are seen as critical for the establishment of a demonstration site in Germany and the transposition of the European CCS directive into German law in a timely manner. Such a process includes "public acceptance", which is a phase beyond that of "public awareness" and "public ownership" of the Underground Space for storage: The main fair for the people is the CO_2 or CH_4 degassing at surface, as well as the fluids injection related seismicity.

The best results with the local population are obtained in cases in which communication and involvement with the local population are begun during the initial stages of establishment of a project (www.terrascienza.it, Quattrocchi and Boschi, web article, January, 2012).

Public opposition to storage of CO_2 or CH_4 in geological formations is on the rise in regions selected for further detailed geological investigations. Most exploration activities or demonstration plans have already been postponed or cancelled for CO_2. A single project from Vattenfall at Jänschwalde in the German state of Brandenburg is currently proceeding (Gabriela Von Goerne, personal communication). For More than 2 years (2009–2011) international observers have been struggling to grasp the complicated political games in Germany surrounding the country's transposition of the EU Directive on CO_2 storage and the government's vote was blocked in October, 2011. Public concerns include a number of issues, mostly for the onshore storage (known as Landerklausul, the state clause is what could have made the law an effective block to onshore German CCS deployment), including potential leakage of

CO_2 or brine, pollution of drinking water, degradation of soil (a concern for farmers) and loss of property value. Niedersachen and Schleswig–holstein want to avoid any CO_2 storage within their territories (Bellona Europa news, October, 2011). Brandenburg wants to see the EU-funded demo project Janschwalde happen, yet fears its voters' vangeance in the case that it, as the sole Bundesland, opens for deployment of CCS. Brandenburg, in face of this pressure, has presented the federal government with an ultimatum: either all Lander must be forced to accept CO_2 storage, or none will.

This is occurring today despite the huge storage capacity potential for CO_2 storage in Germany. German storage capacity is estimated at between 6.3 and 12.8 Gt CO_2 (data BGR). The Wuppertal Institute gives an average effective storage capacity of 5 Gt (range 4–15 Gt). These numbers are appropriate for the situation if CCS is seen as a bridging technology in a world moving towards renewables and safe nuclear power.

However, saline aquifers wherever (including those, around 200, found in Italy) are the most promising rock formations for potential CO_2 storage and (as was shown recently) possibly for CH_4 as well [9,10].

If injection of CO_2 is underground inland and not offshore, it results in displacement of brine and an extending pressure front that involves vast underground spaces under densely populated areas. When the gas injection is offshore but near the coast, geophysical and geochemical monitoring of possible geogas leakage and induced or triggered inland seismicity is imperative the same. The ENEL began such inland monitoring for the Alto Adriatico EEPR-ZEPT Project (INGV-ENEL data still confidential).

This knowledge and framework must be taken into account when planning a CO_2 storage project and alternative uses for the surrounding area.

2.8. Geological disposal of radioactive wastes

Wide worldwide researches devoted to the comprehension of an active seismo-tectonical area such as the Italian territory could be very useful in the framework of nuclear waste disposal research application. This research should be however coordinated by dedicated governmental agencies such as SOGIN S.p.A. for Italy (following the Italian Law 31 dated 14-02-2010, which stated the need of the Italian "Nuclear Technological Park", PTN, as a national "near surface" nuclear waste repository site).

These activities, mostly if we are speaking about deep geological nuclear waste disposal (not jet realized fully in any part of the world) are based upon the concepts of "*analogs*" and "*multi-barriers*" (as proposed by the early Italian School created at CNEN and after ENEA during the 1960–1980s) [1,37–40] could be addressed to nuclear waste disposal. The recent Erice International School reworked and highlighted these concepts.

As for CO_2 or CH_4 geological storage and for geothermics, also for nuclear waste disposal, the disciplines of fluid geochemistry and structural geology are the key tools in this framework, including the concept of "natural barriers", mainly geochemical, that are considered to have dual capacities for diluting and dispersing and/or confining radio-nuclides (i.e., the reducing barriers are able to immobilize the transport of radio-nuclides [40]). Both important properties are considered for low-level, short-lived radio-nuclides that are placed in the repository near the surface or below it. On the other hand, the final "geological disposal" target for the isolation of long-lived, high-activity radio-nuclides (which are defined as High Level Wastes – HLW-), is their confinement in deep geological formations. HLWs make up 5% of the total radioactive waste produced by a typical industrial country (the main portion is from medical care and hospitals, [38–40]).

With respect to the confinement capacity of geological barriers, the early ENEA geological school (Mittempherger and Brondi, personal communication) was categorical: "*Every radionuclide migration from a deep repository in a well-selected geological formation to the superficial environment is null*". This sentence could be challenging for the future research worldwide but it is still not supported by rigorous and enough number of scientific "peer review" papers.

Moreover it is very interesting to correctly understand the message coming from the Yucca Mountains project [42] and references herein. After 20 years of research and a lot of money spent, it finally resulted a failure. This failure was due to the wrong choice of a simple structural geology work package: the repository site was too close to a recent volcanic unrest activity outcrop. At present, for example, the French Nuclear Waste management and its strategic research group have adopted (in part) the Italian findings [38–40]. The French project for the disposal of High- and Intermediate-Level Long-Lived Waste (HILW-LL) is based on a geological repository that was excavated some 500 m below the surface in a clay formation [38–40]. It is currently being thoroughly investigated at the surface and in an underground laboratory at Bure, France. The R&D program has demonstrated the feasibility of the waste disposal project and is now gathering valuable information on the mechanical, hydrological and thermal behavior of the clay formation. A transposition zone was defined that has geological properties that were evaluated as similar to those encountered in the laboratory and particularly suitable for waste disposal. Within this zone, a restricted area (defined ZIRA) was then selected, where 3D seismic and other surveys are currently being carried out to achieve a detailed sedimentary, hydrological and structural description. Other possible underground uses of the formation below the planned repository and methods to protect the long-term record of disposal activities are also being investigated. These activities are enabled by a clear framework that sets a goal of license application by 2015 and commissioning by 2025 for the underground repository in France.

Several years later the ENEA school findings during the '1980s, the development of studies on "*natural analogs*", such as uranium mobilization along faults [36], has led to the positive conclusion asserted by CNEN-ENEA during the 1970s (i.e., Project PAS-SGRIF, laboratory LRRR and geochemical laboratory AMB-MON-PAS in the 1980s). Now, 20 years later, the concept of "*natural analogs*" has also been reworked for geological CO_2 storage; these teaching ideas are actually very useful today [1]. Therefore, the Italian research have reinitiated the exploration of the isolation potentiality of clay formations in Italy and elsewhere. We have also reworked the well logs [19,20] within the framework of our synergistic underground-storage and geothermic catalog in Italy for a sound energy mix.

When it comes to assessing the safety of geological disposal of radioactive waste, a major cause of uncertainty is the long period of time under consideration (many hundreds of thousands of years, i.e., see IAEA-TECDOC-1243 report). For many years, the worldwide scientific community has recognized that "natural analogs" represent the best, if not the only, option for long-term hazards assessments (of the same order of magnitude as the storage period necessary for HLW, i.e., hundreds of thousands years). It is possible to model, step by step, the natural processes that are acting on the water, rocks, and soil bodies of the geo-sphere. They are similar to those processes that are thought to act on a deep nuclear waste repository and are also active over long time spans and under the different earth crust evolution and conditions that are present within 2–3 km (including seismic events). These natural analogs should progressively provide further constrains the soundness of certain rocks to retain underground radio-nuclides in a fix position, involving progressively more scientists of various disciplines in research on radioactive waste disposal and the development of safe disposal options.

Natural analogs are also providing clear evidence for the reliability of geological disposal that is also useful for regulators and for public acceptance. Since the 1980s, natural analogs have been an important theme of European Community research within the framework of the CEC R&D programs. Successive national and international programs have regularly focused on the demonstrative role of natural analogs as the main confirmation tool for experimental and modelling activities. Countries have applied the results derived from studies on natural analogs to their own geological formations of own interest. Generally speaking, the formations under consideration have been granitoid rocks, salt and clay: the exact opposite rocks with respect the storages for CO_2 or CH_4. All of these formations appear to have good possible long-term capacities for isolating dangerous wastes [38–40], but these statements require more work by the geological research. However, clay formations are the most promising because they may play at least two roles with regard to the different options considered for waste disposal, namely (i) direct waste isolation (i.e.,. bentonite) and (ii) isolation by different strata of the "storage complex" host rocks surrounding the waste, namely the geochemical barriers or similar. More literature is strongly necessary. With regard to clay, perturbation processes have been studied extensively (especially in Italy) as analogs of processes that could affect the long-term safety of geological radioactive waste repositories [39,40]. The general results of those early studies demonstrate that clay repositories eventually undergone tectonic uplift and consequent erosion do not lost the original isolation conditions at depths, moving only of a few meters from the final topographic surface. As a general conclusion of those studies, it was highlighted the fact that the "analogs" demonstrate that "geological disposal" of high-level, long-lived radioactive waste assures the long-term safety of future generations [39,40]. They also offer an effective tool for the development of models according to realistic (and not fanciful) approaches. Repository safety is predominantly determined by tectonic evolution. Basing on this cataloging, the next steps of our researches are tentatively approaching to merge this information with the others belonging to the underground space uses. Criticalities could arise during the research phase of a possible deep geological storage sites for HLW in Italy, which is a geodynamically active country. The research activities already accomplished could be then useful at least for the identification of one single out "European geological HLW site" (within EURATOM Projects). Furthermore, our intention is to upgrade the IAEA prerequisite criteria, via implementation of GIS catalogs already begun to gain new helpful information to be exploited also for these purposes.

3. Conclusions

In densely populated countries, there is a lack of important elements needed to plan "low-carbon" energy production in restricted areas. Some of the important prerequisites needed are (i) underground space for storage and geothermal exploitation, (ii) water at the Earth's surface, (iii) public acceptance, and (iv) scientists dedicated to each technology. The inclusion of new technologies such as CO_2 Capture and Storage (CCS) represent not only one of the commonly accepted way to reduce greenhouse emission, but one of the most rapid and reliable response to a continuously growing energy demand.

The idea to develop a strategic mixed-energy plan is growing in the world, especially for densely populated countries such as Italy, but the evaluation should be done by exploiting the concept of Energy Density Potential in Land (EDPL) which could reach, for new geothermal technologies also a maximum level of 800 [GW h/ha/year], with respect to negligible values of solar and wind renewable technologies. We tentatively tried these calculation for a densely populated region as Lazio, in Italy.

Such a plan of a sound regional mixing to produce energy represents also a fundamental tool to solve the problem of rapidly increasing CO_2 emissions. The inclusion of new technologies such as CO_2 Capture and Storage (CCS) adds "noisy" variables to the "underground" system available for electricity power production technologies, but it could be synergic with geothermal energy production and viceversa. Moreover not only conflicting uses are generated between CO_2 and CH_4 storage: a lot of methods and monitoring/verification techniques are common. Good and ancient school for geogas storage is coming from nuclear waste disposal: part of the literature could be common.

Therefore, the need for a mixed-energy plan has become urgent. Such a plan should take into account a strategic use of the underground that allows the coexistence of different technologies that are able to produce "clean" electricity. These technologies include:

- clean coal power plants combined with CCS technology (e.g., following EU-ZEP Platform working-group directions [4]);
- CH_4 storage in natural reservoirs as strategic reserves to be readily available both during failures or stoppages of outside pipelines and for seasonal natural gas storage availability modulation;
- last-generation nuclear power plants with safe HLW geological disposal and with at least one geological waste disposal site for each continent, which could be associated to more than one national "near-surface" provisory nuclear waste disposal sites (such as the "Parco Tecnologico Nucleare" in Italy, El Cabril in Spain, D'Auge in France, and Olkiluoto in Finland);
- renewable energy sources possibly including low-space-consuming technologies such as deep geothermal energy (i.e., the new generation of technologies for high-to-medium enthalpy exploitation).

The arrangement of a strategic mixed-energy plan need also to develop multidisciplinary research groups that integrate various fields of research including Earth Sciences, modelling and mathematics as well as socio-economic sciences.

This new approach to the low-carbon power-production problem will bring together, and not divide, the different lobbies and scientific communities.

In our intentions a first approach could be the development of Dedicated Geographic Information Systems (D-GIS, in our case called the "Underground geological storage and geothermal structures catalog for low-carbon energy exploitation in a sound energy-mix in Italy"). These can represent useful planning tools to evaluate synergies and/or conflicts among different deep (between 500 and 5000 m depths) underground uses that are linked to different energy production technologies.

Therefore, we built a D-GIS to organize a regional planning of the soundest energy mix, case, by case.

We presented and discussed a detailed data set stating with the Lazio and Campania Italian regions. Results show that suitable areas where to establish geologica storage and geothermics could be found even in the framework of complex geological setting as the Italian one: also in so difficoult geodynamical settings, geogas geological storage and geothermics could be well exploitable within the framework of low-carbon technologies for electric energy production. More critical is the choice for a possible European geological nuclear waste disposal site. On the other hand, the concept of natural nuclear waste disposal in natural geological–geochemical barriers such as clays should be reworked and exploited newly as in the past (1970, 1980).

Moreover, this study could represent a useful tool for policy makers and environmental managers who are capable to improve the guidelines of underground site selection for all of the technologies contemplated by the IEA Road Map 2009.

In any case, upgrading and increasing of post-graduate specialization in this discipline, namely "underground use" research, is imperative. Therefore, it is important to increase the training of young researchers. This can be done by increasing (i) dedicated courses at engineering faculties all over the world and (ii) dedicated and customized international schools addressed to the synergistic use of underground areas to produce low-carbon electric energy.

The new welcome technology is CO_2 Capture and Storage (CCS), which was widely accepted to use underground worldwide, and in particular in Europe, after the reception of the European Directive 31/2009 on CO_2 Geological Storage: now it is operative in Italy, among the first, after their statement in October, 2011.

Another great effort is the periodic revision and updating of Annex 1 and Annex 2 of the EU Directive. Particular attention has been focused on the management of the public acceptance of the "associated and perceived risks" for (i) CO_2 leakage at the surface as seepage, and (ii) fluid-induced seismicity during and after gas injection. These risks are the same for natural gas storage and geothermics, mostly when fluids are injected underground.

Newspapers and media communication play a major role in promoting and disseminating knowledge concerning these themes. They should correctly communicate that the degassing and leakage risks could be negligible or minimized if a detailed storage site selection was accomplished under rigid and standardized criteria. The media therefore have a big responsibility and is imperative to avoid last-minute "scientific journalists". The experience acquired studying the Diffuse Degassing Structures (DDSs), which are widespread in Italian territory, provided the opportunity to be able to understand, manage and communicate this type of natural hazard, common to different geological storage underground and to geothermal exploitation.

The exploitation of CCS technology actually has the advantage with respect to the natural gas (CH_4) underground storage that CO_2 is reactive and soluble in groundwater. These concepts, and those related to natural gas storage and pipelines, need to be discussed and explained to the people.

Monitoring protocols for natural gas and CO_2 storages or deep geothermics are similar to those used for seismic and volcanic surveillance. These activities have been performed by the scientific community in geodynamically active countries, as Italy, here since decades as duties within the framework of the Italian Civil Protection Department Projects, and standardized monitoring procedures were already tested and structured in early warning systems which are capable to be accomplished within a short time and throughout the Italian territory.

The absence of knowledge of basic and simple concepts could generate panic for the public acceptance of this methods. Moreover this could represent an obstacle if any storage sites is "imposed" to the public rather than "proposed", especially during the appraisal of the feasibility studies. These studies should involve NGOs as participants in the IEA Road Map 2009 for underground use policies in a new low-carbon world (i.e. www.OsservatorioCCS.org).

According to our vision, by leaving the management of "*Underground Space*" use problem (including liability, authorizations and monitoring) mainly to public research and public authorities, the different power-generation technologies could develop their "low-carbon revolution" without competition.

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Appendix A. GIS data and strata

- Geology:
  - stratigraphy, lithology and mineralogy;
  - structural characteristics;
  - geotectonic characteristics.
- Tectonic and seismicity:
  - historical seismicity at the site;
  - occurrence of quaternary faults at the site and the age of latest movement;
  - evidence of active tectonic processes, such as volcanism;
  - estimate of the maximum potential earthquake within the geological setting.
- Hydrogeology:
  - major water uses;
  - major discharge and extraction points;
  - groundwater flow velocity and direction.
- Geochemistry:
  - physicochemical features of groundwater;
  - the presence of natural colloids and organic materials;
  - the presence of geochemical barriers (pH, Eh, temperature, fluids) mostly along fault systems.
- Surface processes:
  - topography;
  - location of surface water bodies;
  - landslide hazards;
  - flooding hazards;
  - upstream drainage areas.
- Land use:
  - land resources, uses and their jurisdictions.
- Transportation:
  - Highways and roads networks.
- Meteorology:
  - wind and atmospheric dispersion characteristics;
  - precipitation characteristics;
  - extreme weather phenomena.
- Human-induced events:
  - location of hazardous installations;
  - energy and information transportation grids (especially pipelines)
  - locations of airports;
  - locations of routes with frequent movement of hazardous materials;
  - energy and mineral resources;
  - past and present drilling and mining operations in the vicinity of the sites.
- Population distribution:
  - territorial population density.
- Protection and environment:
  - locations of national parks and areas with historical monuments and archeological findings;
  - surface water and groundwater resources and quality;
  - terrestrial and aquatic vegetation and wildlife (particularly endangered species).

The following data were recently added into the GIS database:

– monthly average rainfall in Italy;
– monthly average soil temperature in Italy;
– Italian railway networks and train-stations;
– Italian highway networks;
– Italian road networks;
– Italian land use;
– landscape features, archeological features;
– hazardous installations;

hydrography of Italy.

References

[1] Mele G, Cantucci B, Procesi M, Sciarra A, Nardi S, Boschi E, Densely populated settings: the challenge of siting geological facilities for deep geothermics, CO_2 and natural gas storage, and radioactive waste disposal underground coexistence and synergies for a sound energy mix in the post-kyoto era. In: Quattrocchi F. editor. Miscellanea INGV, vol. 11; 2011. 104p, ISSN 2039-6651.
[2] European Commission. World Energy Technology Outlook – 2050; 2006. <http://ec.europa.eu/research/energy/pdf/weto-h2_en.pdf>.
[3] Dong C, Huang GH, Cai YP, Xu Y. An interval-parameter minimax regret programming approach for power management systems planning under uncertainty. Appl Energy 2011;88:2835–45.
[4] Quattrocchi F. Among other authors expert reviewers. IPCC report carbon dioxide capture and storage. Cambridge University Press; 2005. 443p. ISBN-13 978-0-521-86643-9, ISBN-10-0-521-86643-X, ISBN-13 978-0-521-68551-1, ISBN-10-0-521-68551-6.
[5] Cantucci B, Montegrossi G, Vaselli O, Quattrocchi F, Perkins EH. Geochemical modelling of CO_2 storage reservoirs: the Weyburn Project (Canada) case study. Chem Geol 2009;265:181–97.
[6] Cantucci B, Montegrossi G, Buttinelli M, Lucci F, Vaselli O, Quattrocchi F. Overview of the geochemical modelling on CO_2 capture and storage feasibility studies in Italy. In: Proceedings international conference on "Goldschmidt 2009". Geochimica Cosmochimica Acta; June, 2009 [Abstracts].
[7] Cantucci B, Montegrossi G, Lucci F, Buttinelli M, Vaselli O, Quattrocchi F. CO_2 reactive transport simulators in an Italian deep saline aquifer. Epitome 2009;3:292. FIST, 2009, ISSN 1972-1552.
[8] Cantucci B, Procesi M, Buttinelli M, Montegrossi G, Vaselli O, Quattrocchi F. Mineralogy and geochemical trapping of CO_2 in a Italian carbonatic deep saline acquifer: preliminary results. Geophys Res Abstr 2008;10. EGU2008-A-08955.2008 SRef-ID: 1607-7962/gra/EGU2008-A-08955.
[9] Bencini R, Scrocca D, Petracchini L, Vico G, Carminati E, Doglioni C, et al. Natural gas and CO_2 storage in fractured carbonate reservoir, Epitome, vol. 3; 2009. p. 294, FIST, 2009, ISSN 1972-1552.
[10] Bencini R, Scrocca D, Petracchini L, Vico G, Carminati E, Doglioni C, et al. Fractured carbonatic aquifers in Italy: natural gas and CO_2 storage applications. In: Proceedings AAPG symposium the role of fracture and geomechanical characterization in the hydrocarbon industry: middle eastern perspective. Rome, Italy; 28–30 June, 2010.
[11] Angelone M, Gasparini C, Guerra M, Lombardi S, Pizzino L, Quattrocchi F, et al. Fluid geochemistry throughout the Sardinian Rift-Campidano Graben: fault segmentation, seismic quiescence of geochemically "active" faults and new constrains for the selection of the CO_2 storage sites. Appl Geochem 2004;20:317–40.
[12] Pizzino L, Burrato P, Quattrocchi F, Valensise G. Geochemical signature of large active faults: the example, Calabrian Earthquake of the 5 February 1783. J Seismol 2004;8:363–80.
[13] Quattrocchi F. In search of evidences of deep fluid discharges and pore pressure evolution in the crust to explain the seismicity style of Umbria-Marche 1997–1998 seismic sequence (Central Italy). Annali di Geofisica 1999;42(4):609–36.
[14] Quattrocchi F, Buttinelli M, Cantucci B, Cinti D, Galli G, Gasparini A, et al. Very slow leakage of CO_2, CH_4 and radon along the main activated faults of the strong L'Aquila earthquake (Magnitude 6.3, Italy)? Implications for risk assessment monitoring tools and public acceptance of CO_2 and CH_4 underground storage. In: Proceedings GHGT-10, Amsterdam, September 2010. Energy Procedia; 2010.
[15] Pizzino L, Galli G, Mancini C, Quattrocchi F, Scarlato P. Natural Gases Hazard (CO_2, ^{222}Rn) within a quiescent volcanic region and its relations with seismotectonics: the case of the Ciampino-Marino area (Colli Albani). Nat Hazards 2002;27:257–87.
[16] Voltattorni N, Sciarra A, Quattrocchi F. Gas geochemistry of natural analogues for the studies of geological CO_2 sequestration. Appl Geochem 2009;24:1339–436.
[17] Quattrocchi F. Lo stoccaggio geologico di CO_2: stato dell'arte e strategie. Qualenergia 2006;4(1):23–5.
[18] Montegrossi G, Scrocca D, Vaselli O, Cantucci B, Quattrocchi F. Feasibility of carbon capture and sequestration in Italy. Epitome 2009;3:293. FIST, 2009, ISSN 1972-1552.
[19] Quattrocchi, Buttinelli M, Procesi M, Cantucci B, Moia F. Development of an Italian Catalogue of potential CO_2 storage sites: an approach from deep wells data. Geophys Res Abstr 2008;10. EGU2008-A-09717.2008 SRef-ID: 1607-7962/gra/EGU2008-A-09717.
[20] Buttinelli M, Procesi M, Cantucci B, Quattrocchi F. The geo-database of caprock quality and deep saline aquifers distribution for geological storage of CO_2 in Italy Energy 2011;36:2968–83.
[21] Quattrocchi F. Communication strategy for a public information campaign on CO_2 geological storage and on CCS as a whole: the case history in Italy from 2003 to 2008. Energy Procedia 2008;1:4689–96.
[22] Spena A. Early barriers to be removed for deployment of large scale CO_2 capture and storage systems in Europe and in foreign countries, Atti 2 Congresso Nazionale AIGE, Pisa; Settembre, 2008.
[23] Spena A, Borzacchi N, Quaglione M. Problemi gestionali posti in Italia al sequestro della CO_2 dai vincoli infrastrutturali e territoriali: una analisi preliminare, Atti 2 Congresso Nazionale AIGE, Pisa; Settembre, 2008.
[24] Salvi S, Quattrocchi F, Angelone M, Brunori CA, Billi A, Buongiorno F, et al. A multidisciplinary approach to earthquake research: implementation of a geochemical geographic information system for the Gargano site, Southern Italy. Nat Hazards 2000;20(1):255–78.
[25] Quattrocchi F, Capelli G, De Rita D, Faccenna C, Funiciello R, Galli G, et al. The Ardea Basin fluid geochemistry, hydrogeology, and structural patterns: new insights about the geothermal unrest activity of the Alban Hills quiescent volcano (Rome, Italy) and its geochemical hazard surveillance. In: Proc X inter conf "Water-Rock interaction" (WRI-10), Villasimius, Italy; June, 2001, Balkema, vol. 1; 2001. p. 111–4.
[26] Quattrocchi F, Favara R, Capasso G, Pizzino L, Bencini R, Cinti D, et al. Thermal Anomalies and fluid geochemistry framework in occurrence of the 2000–2001 Nizza-Monferrato seismic sequence (Northern Italy): episodic changes in the fault zone heat flow or chemical mixing phenomena? Nat Hazards Earth Syst Sci 2003;3:269–77.
[27] Federico C, Pizzino L, Cinti D, De Gregorio S, Favara R, Galli G, et al. Inverse and forward modelling of groundwater circulation in a seismically active area (Monferrato, Piedmont, NW Italy): insights into stress-induced variations in water chemistry. Chem Geol 2008;248:14–39.
[28] Quattrocchi F, Guerra M, Pizzino L, Lombardi S. Radon and helium as pathfinders of fault systems and groundwater evolution in different Italian areas. Il Nuovo Cimento 1999;22(3–4):309–16.
[29] Liu I, Huang GH. A dynamic approach for non-renewable energy resources management under uncertainty. J Petrol Sci Eng 2000;26:301–9.
[30] Pruess K. On production behavior of enhanced geothermal systems, with CO_2 as working fluid. Energy Convers Manag 2008;49:1446–54.
[31] Quattrocchi F, Bencini R, Cantucci B, Cinti D, Galli G, Sciarra A, et al. ECBM feasibility studies in Italy: state of art and perspectives. In: Proceedings Asian coal bed methane, brisbane, Australia, 25–27 September, 2008; 2009.
[32] Ottiger S, Pini R, Storti G, Mazzotti M, Bencini R, Quattrocchi F, et al. Adsorption of Pure carbon dioxide and methane on dry coal from sulcis coal province (SW Sardinia, Italy). Environ Prog 2006;25(4):355–64.
[33] Spena A. Territorial and infrastructural risk mitigation for large scale deployment of deep geothermics and CO_2 transport and storage technologies. In: Quattrocchi F. Editor with Mele G., Cantucci B. Procesi M., Sciarra A., Nardi S. Boschi E. (2011). Densely populated settings: the challenge of siting geological facilities for deep geothermics, CO_2 and natural gas storage, and radioactive waste disposal. Underground coexistence and synergies for a sound energy mix in the post-kyoto era. Miscellanea INGV, 11, ISSN 2039-6651; 2010. 104p, p. 81–82.
[34] Jones DG, Strutt MH, Beaubien SE, Lombardi S, Voltatorni N, Baubron JC, et al. Soil gas as a monitoring tool of deep geological storage of carbon dioxide: results from the Encana EOR project in Weyburn, Saskatchewan (Canada). J Am Chem Soc (Abstract) 2003;226:139.
[35] Riding J, Rochelle C + Among the 44 contributing authors: Quattrocchi F, Bencini R, Cantucci B, Cardellini C, Cinti D, Galli G, Granieri D, Pizzino L, Voltattorni N. The IEA Weyburn CO_2 monitoring and storage project. Final report of the European research Team British Geological Survey Research report, RR/05/03. 54p (ISBM 085272 507 8). BGS, Keyworth, Nottingham; 2005.
[36] Walia V, Quattrocchi F, Virk HS, Yang TF, Pizzino L, Bajwa BS. Radon, Helium and Uranium in some thermal springs located in NW Himalayas, India: mobilization by tectonic features or by geochemical barriers. J Environ Monitor (JEM) 2005;7:850–5.
[37] Miller W, Alexander R, Chapman N, McKinlet I, Smellie J. Geological disposal of radioactive wastes and natural analogues. "Waste Managment" Series, vol. 2. Pergamon; 2000.
[38] Toxic waste disposal: a geological approach. In: Proceedings of international school of earth and planetary sciences, Siena; 1999. RICCI CA, ISSN 1122-8830.
[39] Benvegnù F, Brondi A, Polizzano C. Natural Analogues and Evidences of long-term isolation capacity of clays occurring in Italy. Internal report directorate-general science, research and development, EUR 11869 EN, Published by the CEC directorate-general telecommunications, information industries and innovation, L-2920 Luxembourg; 1988.
[40] Benvegnù F, Brondi A, Polizzano C. Natural analogues and evidence of a long-term isolation capacity of clay occurring in Italy. Contribution to the demonstration of geological disposal reliability of long-lived wastes in clay 1989;8:101, ISBN 92-825-9096-8.
[41] Evans DJ, Chadwick RA. Underground gas storage: an introduction and UK perspective. In: Evans DJ, Chadwick RA. editors. Underground gas storage:

worldwide experience and future development in the UK and Europe, vol. 313. London, Special Publication: Geological Society; 2009. p. 1–10.
[42] Dobson PF, Kneafsey TJ, Sonnenthal EL, Spycher N, Apps JA. Experimental and numerical simulations of dissolution and precipitation: the implications for fracture sealing at Yucca Mountain, Nevada. J Contamin Hydrol 2003;62–63:459–76.
[43] Quattrocchi F, Pizzi A, Gori S, Boncio P, Voltattorni N. The contribution of fluid geochemistry to define the structural pattern of the 2009 L'Aquila seismic source. Ital J Geosci 2012; IJG-2011-0110-R1, in press.
[44] Spena A. Rinnovabili e paesaggio. Usi multipli della risorsa idraulica, Primo Rapporto annuale, Consorzio Tiberina, Roma; 2010.
[45] Pallabazzer R. Parametric analysis of wind siting efficiency. J Wind Eng Indust Aerodyn 2003;91:11.
[46] Cinti D, Tassi F, Procesi M, Quattrocchi F. Fluid Geochemistry and geothermometry in the Wastern sector of the Sabatini Volcanic District and the Tolfa Mountains. Chem Geol 2011;284:160–81.
[47] Carlino S, Somma R, Troie R, De Natale G. The geothermal exploration of the Campanian volcanoes: historical review and future development. Renew Sustain Energy Rev, in press.
[48] Quattrocchi F., Boschi E. (2011) La Sfida del Sottosuolo. Quotidiano Energia, N. 233, Anno 7, p 7.