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Storage potential evaluation of eastern Mediterranean area as final step of the full chain assessment

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Abstract

The last step of the CCUS full chain is represented by geological storage, when the CO2 is injected, via injection wells, into the deep sub-surface at a carefully selected site (such as a saline aquifer or a depleted oil/gas field). This work describes the methodology, and several preliminary results adopted by the AURORA project (https://aurora-heu.eu/) to select suitable storage sites for the CO2 source plants of the project, located in the Mediterranean area. The selection will be based on a comprehensive set of criteria that has been extensively described in numerous publications, tested in various projects, and adopted by the CO2 storage atlas of several European countries (as Norway and UK) (Riis & Halland, 2014; Halland et al., 2014; https://www.co2stored.co.uk/home/index); results has been compared to the previous calculation and evaluation performed for the same areas.
The presented work had the aims to review the main strategies adopted for site selection and evaluation by previous projects, describes the geological areas suitable for storage for the Aurora project and their potential, and summarizes the methodology that will be used for evaluation (ranking criteria). Considering that storage wasn't included in the LCA provided by the AURORA project, further goals will be to evaluate criteria for the commercial maturity of the sites.

Keywords: capacity evaluation, geological storage, southeastern Europe, Aurora project

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1. Introduction

During the last fifteen years, several European projects have focused on the evaluation of the potential of CO_2 storage and on the storage capacity calculation of the European territory. In the previous project appraisal of storage potential was focused on saline aquifers, both in the siliciclastic and in the carbonate portion of the stratigraphic succession; more recently, the potential of depleted gas reservoirs has also been evaluated (Geocapacity and CO2Stop https://setis.ec.europa.eu/european-co2-storage-database_en).
Since the Aurora project dedicates the WP5 to the full chain feasibility study project mainly focused on the capture

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and transport phases, the sites evaluation in southern Europe will support this analysis by the selection of suitable storage sites, according to geological and technical criteria, as well as by an evaluation of their commercial maturity in the framework of a more comprehensive evaluation. The site selection and evaluation will be based on a comprehensive set of criteria that has been extensively described in numerous publications, tested in various projects, and adopted by the CO2 storage atlas of several European countries (as Norway and UK) (Riis & Halland, 2014; Halland et al., 2014; https://www.co2stored.co.uk/home/index). The adopted methods provides a double approach. On one side it evaluates the site from a geological point of view (considering some geological aspects as a function of data quality). On the other, it evaluates the state of development of the site from a technical-economic point of view, including the capacity estimation (including the concept of SPE SRMS). The adopted methodology (in common with the most recent EU project) has the aims to be comparable as much as possible with the already performed evaluation of the other provinces/sites of Europe, with the aims to homogenise the results. This choice will favour standardization of the adopted criteria for site selection in European countries that still does not have a comprehensive storage atlas; on the other side, as this methodology includes some economical/commercial aspects, it will provide a more complete full chain analysis.

2. Feasibility study experiences from other projects

The methodology adopted to complete the full chain evaluation within the AURORA project will be based on the experience gained during previous EU projects and existing CCS cluster projects in Northern Europe. In fact, there is growing interest in the evaluation of the full chain of CCUS, since this approach can better define potential issues and total costs. Among these projects, the recent Strategy CCUS (https://www.strategyccus.eu/) developed a complete methodology that was applied to eight potential onshore storage sites in Europe, based on an approach for new ICCS clusters (also known as industrial hubs). This project reviewed existing methodologies from a storage point of view, proposing a synthesis and several recommendations. The recommended approach was based on several documents, including: the Norwegian Storage Atlas, the UK CO2 Stored database, the Society of Petroleum Engineers - Storage Resource Management System or “SPE-SRMS” (SPE, 2017) and, for storage capacity calculation, the American analytical equations for capacity (from CO2 Storage Atlas of USA) (NETL, 2015).
The CCUS Strategy approach is a common storage methodology which was applied to the promising regions of the project. It combines a qualitative suitability appraisal and a capacity estimate. Suitability covers all technical aspects of storage, from reservoir capacity and quality to seals, faults, and wells. The Boston square score was adopted for the CCUS Strategy appraisal. Particular attention was dedicated to the capacity estimate, based on the approach of the quantitative resource pyramid (Bachu, 2003). Four ranking degrees were defined that represent the increasing maturity of data and understanding of the potential storage capacity, along with a progressive reduction of the scale that ranges from a regional approach to the targeted storage site candidates. These four levels are comparable with existing evaluation schemes (CSLF TERR; SPE, 2017), which means that the results and overall evaluation can be compared with those from other projects.
There are other comprehensive global evaluations available, such as the CO2 Storage Resource Catalogue (CSRC, https://www.ogci.com/ccus/co2-storage-catalogue) that includes a global view of the commercial readiness of CO2 storage resources in key markets. Even in this case, this database classifies the resource maturity of published storage sites based on evaluations using the SPE-SRMS approach. The common use of the SPE-SRMS reduces the subjective nature of resource assessment and helps in the comparison of resource potential and maturity. The CO2 Storage Resource Catalogue and Storage Resources Management System includes CO2 storage in saline aquifers and in depleted or partially depleted oil and gas fields, some cases of CO2-Enhanced Oil Recovery (CO2-EOR), but excludes other storage options such as unmineable coal, mineralisation, and organic-rich shales. Moreover, it does not provide information for the areas of interest of the AURORA project.
Recently the storage potential of basalts has been described in results from the CARBFIX project (Snæbjörnsdóttir et al., 2020; Raza et al., 2022). These are based on the surface area of basaltic rocks (volcanic and plutonic) on the continents, on the ocean floor as well as specifically for Europe and the United States of America. Recently Koukouzas et al. (2019) proposed some exploratory studies on basaltic rocks outcropping in central Greece to evaluate potential CO2 storage. In general, this technology is at a very early stage of research and has very high costs; in any case an evaluation of these new technology will be included in the AURORA project.

3. Potential areas for storage in AURORA project

3.1 The Adriatic Sea region

The Adriatic Sea geological province spans from the coast of Venice in the north to the Gulf of Taranto in the south. From a geological perspective it represents the foreland/foredeep domain of three distinct fold and thrust belts, the Southern Alps in the north, the Apennines to the west and the Dinarides in the east (Bigi et al., 2013; Saftic et al., 2019; Proietti et al., 2022). The three orogens, associated with different subduction zones, formed in the broad and articulated framework of the N–S convergence between the European and the Adriatic plates (Carminati and Doglioni, 2012). The Adriatic Sea geological province is one of the most important regions of natural gas and oil production in the entire Mediterranean area. Indeed, starting from the early 1950's about one hundred small gas fields have been discovered in the Italian part of the basin, mainly within Pliocene clastic sequences; a similar situation exists on the Croatia site (Casero & Bigi, 2013; Zelilidis and Maravelis, 2015).

Recently, the Adriatic Sea has attracted much attention also for the geological storage of CO2, due to the occurrence of well-known physical traps (confirmed by the now mostly exploited hydrocarbon reserves) and deep saline aquifers within both the carbonate and siliciclastic sequences (Civile et al., 2013; Volpi et al., 2014; Saftic et al., 2019; Proietti et al., 2022). These geological aspects, together with the presence of different industrial centres along the coasts (representing a relatively close source of CO2) and with the already existing infrastructure for the management and distribution of natural gas (gather centre, pipelines), make the Adriatic Sea geological province a promising area for CO_2 storage.

During the last fifteen years, several European projects have focussed on the evaluation of the potential of CO_2 storage and on the storage capacity calculation of the European territory. The projects have been based on common shared criteria and calculated both the theoretical and effective storage capacities (Bacu et al., 2007; Bachu, 2015; CO2CRC report, 2008). According to these studies (Donda et al., 2011; Donda et al., 2013; Civile et al., 2011; Poulsen et al., 2015; StopCO2 database; Proietti et al., 2023) the Adriatic Sea province represents a valid potential storage province. In the Geocapacity project (Vangkilde-Pedersen et al., 2009) appraisal of storage potential was focused on saline aquifers, both in the siliciclastic and in the carbonate portion of the stratigraphic succession; more recently, the potential of depleted gas reservoirs has also been evaluated (CO2Stop https://setis.ec.europa.eu/european-co2-storage-database_en) (Fig. 1).

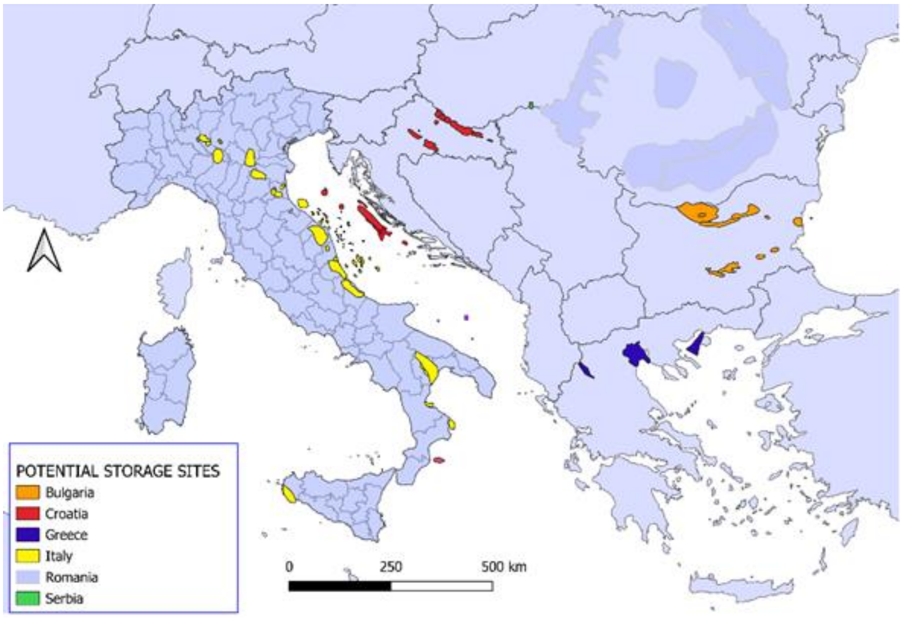

Figure 1 - Location of potentially suitable sites for CO2 geological storage in Southern - Central Europe (data from Geocapacity and CO2Stop database, Proietti et al., 2022, Saftic et al., 2021; KouKouzas et al., 2016).

3.2 The onshore southern Balkan area

Results from the Geocapacity and CO2stop projects included other areas of potential interest for the AURORA project: in particular, the onshore Balkan area, which includes the orogenic system of the Balkan chain (the so called "mobile Europe"), formed and largely influenced by the Alpine orogeny. For the Aurora project we will include potential areas belonging to onshore northern Greece, Croatia and Romania (KouKouzas et al., 2009; Vulin et al., 2023; Cormos, 2016). The total CO_2 storage capacity of these countries was already evaluated in several EU projects (CASTOR, CCUSTRATEGY). The most outstanding features in "mobile" Europe are the high mountain chains of the Carpathians and Dinarides that surround the southern Pannonian Basin, where the main storage target is represented by Miocene deposits that host the most important aquifers and hydrocarbon reservoirs (Fig. 1).

3.3 The Ionian Sea and Eastern Greece

Southeastern Europe includes areas of potential interest: in particular, the onshore Balkan area, which includes the orogenic system of the Balkan chain (the so called "mobile Europe"), the onshore northern Greece, Croatia and Romania (Tasianas & Koukouzas, 2016; Kukouzas et al., 2009; Cormos, 2016). The total CO2 storage capacity of these countries was already evaluated in several EU projects (CASTOR, CCUSTRATEGY) and has been reviewed. Greece offers opportunities for CO_2 geological storage such as deep saline aquifers in the Greek Mesohellenic basin and existing depleted hydrocarbon fields in the Tertiary sedimentary basin of Prinos.
The Mesohellenic basin and its Grevena sub-basin area offer CO_2 storage opportunity for the Western Macedonia industrial cluster due to its 50 km proximity and the occurrence of deep saline aquifers (Koukouzas et al., 2009). It is partly located in Northern Greece and partly in Albania and was formed from Middle Eocene to Upper Miocene. Koukouzas et al., 2016 estimated the theoretical CO2 storage capacity for the Mesohellenic basin in the Grevena area to be about 700 Gt.
Along the eastern coast, the Geocapacity project assessment of CO_2 storage capacity in deep saline aquifers in Greece also includes the Tertiary sedimentary basin of Prinos (GeoCapacity 2009). The potential storage site consists of the partially depleted Prinos oil reservoir. The Prinos basin formed at the southern end of the Rhodope Massif, between Thassos island and the mainland; the main axis is oriented NE-SW, and the basin covers an area of about 800 km2.

3.4 Basalt area for Mineralization

Recently the storage potential of basalts has been described in results from the CARBFIX project (Snæbjörnsdóttir et al., 2020; Raza et al., 2022). These are based on the surface area of basaltic rocks (volcanic and plutonic) on the continents, on the ocean floor as well as specifically for Europe and the United States of America. Recently Koukouzas et al. (2019) proposed some exploratory studies on basaltic rocks outcropping in central Greece to evaluate potential CO2 storage. In general, this technology is at a very early stage of development and has very high costs; in any case, an evaluation of these new technologies will be included.

4. Adopted Methodology

Site selection in the described areas will be performed in the AURORA project following the same proposed by previous EU projects, starting from the results of the more recent one, CCUS Strategy. Consequently, the proposed methodology represents a synthesis of the main methods adopted in the past by previous projects. For this reason, it can be considered a practical and comprehensive approach to the problem. Moreover, this choice will favour standardization of the adopted criteria for site selection in European countries and, as this methodology includes some economical/commercial aspects, it will contribute to a more complete full chain analysis.
From the storage side the method provides a double approach. On one side it evaluates the site from a geological point of view (considering some geological aspects as a function of data quality). On the other, it evaluates the state of development of the site from a technical-economic point of view, including the capacity estimation (introducing the concept of SPE SRMS).

In this way the method provides two scores, based on two evaluation procedures:

- For geological aspects (adopting the Boston square analysis approach)
- the economical evaluation is based on the SPE SRMS, which includes and evaluates commercial potential. In this way it includes some technical aspects, such as the occurrence of infrastructure, the distance from the CO2 source, etc. and their economical evaluation.

4.1 Geological aspects

The list of parameters that will be evaluated in the AURORA approach for site selection will be scored for both attribute suitability and data quality and is plotted to provide an overview of the site and, at the same time to show potential data gaps. This approach allows for a qualitative analysis for data suitability and data quality (both evaluated as an index 1, 2 and 3) of a suite of parameters (Koukouzas et al., 2021) that evaluate reservoir capacity and seal quality, injectivity and the faults occurrence. For each criterion, a score will be assigned based on the kind of data that determine the total quality (seismic, core, logging, and literature), as well as their abundance and affordability. High values indicate good attributes, as, for example, high capacity, good petrophysical characters of reservoir, an efficient seal and few or absent problematic aspects as uncertainties connected to occurrence of faults or ancient wells. The criteria used in this analysis are summarized in the Table 1 (from Koukouzas et al., 2021).

4.1 Capacity

For capacity evaluation the AURORA project has adopted the four-tiered pyramid based on the pioneering North American CSLF approach (Bachu et al., 2007), with levels mapped to CSLF and SRMS terminology (SPE, 2017). This capacity evaluation is then included in the previous analysis for each site (Fig. 2).
The capacity quantification will be based on available data, integrated, where possible, by new data and calculations. The calculations will be expressed, when possible, using the common P90 - P50 - P10 probabilistic estimation approach and will be based on available databases (Geocapacity, CO2Stored) and other more recent published data. The capacity values will be evaluated using the quantitative resource pyramid approach consisting of four levels. Each level represents the increasing maturity of data and understanding about the potential storage capacity, from regional first approximations to targeted storage site candidates. The described tiers are compatible with existing schemes (CSLF TERR Techno-Economic Resource-Reserve TERR, SPE SRMS), allowing outcomes to be transferred to equivalent classifications:

• Tier 1 - Regional assessment. This value is equivalent to Theoretical capacity from Bachu et al. (2007), adopting a generic global or regional SEFs (Storage Efficiency Factor).

• Tier 2 - Discovery assessment or effective capacity, obtained using detailed SEFs, defined on lithologies and kind of potential reservoir (DSA, deep saline aquifer, DHF depleted hydrocarbon field, and Basalts deposits)

• Tier 3 - Prospect assessment; equivalent to Contingent and/or Practical capacity. To reach this level, capacity calculation should be based on existing (or targeted data acquisition) sufficient to build a simple geomodel for simulation and proposed injection well location.

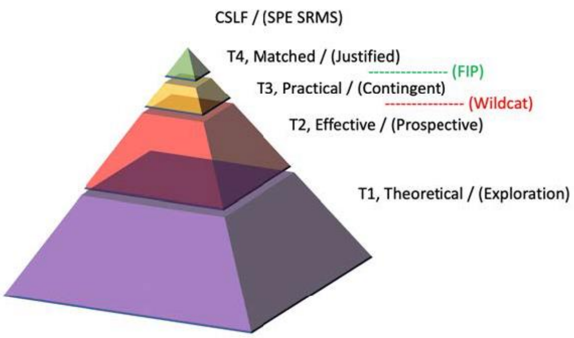

Figure 2 - Four-tier capacity pyramid with CSLF and SRMS terminology (from Koukouzas et al., 2021, modified)

• Tier 4 - Site assessment; equivalent to Justified/Approved/On Injection (Matched capacity). It consists of the capacity value obtained from elaboration and analysis of high-quality data to build a detailed geomodel for reservoir simulation.

5. Integration in the full chain

The evaluation of potential storage sites should consider the possibility to create an integrated capture, transport, and storage chain. Considering this, the described analysis will be integrated with the evaluation of the hub and CO2 transport assessment. Considering that costs of storage depends on the criteria used for site selection and evaluation, at the end of this process, geological sites with a best evaluation will correspond with the ones requiring minimum costs (both OPEX and COPEX), that will be calculated. For example, considering the type of field (oil and gas depleted field vs saline aquifers) depleted fields generally require lower cost, if a field contains legacy wells that can be re-used. Re-use is cheaper than building new wells, even with costs associated with closing unusable wells and mitigating the risk of CO2 leaking from old wells. Other constraints are the geological characteristics of the field (e.g. determining the average CO2 injection rate per well), the field depth, its location (on- or offshore) which are included. All these aspects contribute to determine CAPEX cost, mainly on the drilling phase, that can include drilling of new wells or the re-use of older ones or both, in the case of the need of more than one injection well (low permeability and low infectivity of the reservoir).

During the operational time of the field, main costs are represented by injection activity and monitoring. Injection cost considers mainly the management of the wells, whereas monitoring costs include activities to measure, monitor and verify stored CO2 for safety and regulatory purposes.

The operational lifetime of the storage site is generally considered of 20 years; after that, fields and wells are closed and handed over to the regulators. The storage costs also include the costs of monitoring and verification of the field for a period of 20 years after its economic lifetime has passed. Storage costs also include other liability fund, to cover potential uncertainties during operational phase.

6. Policy and regulation

The integration of policy and regulatory aspects is critical to properly define the main strategic criteria linked to a full life-cycle assessment of CCUS, given that the existence of a well-defined set of rules builds a favourable environment for investors and overall CCUS development. This can be described at the European and national levels.

At the European level, the *Directive on the geological storage of* CO_2 (Directive 2009/31/EC) establishes the legal framework for the development of geological storage of CO_2 as a measure to mitigate the effects of climate change. It covers all CO_2 storage in geological formations in the EU over the entire lifetime of the storage sites, including guidance to ensure that they are environmentally safe. This Directive also contains indications about capture and transport, the other two components of CCS. These activities are already covered by other existing EU environmental legislation (such as the Environmental Impact Assessment and Industrial Emissions Directives), however amendments introduced by the CCS Directive add some specific aspects. Capture and transport are described in several articles in the CCS Directive, mainly related to environmental safety, transnational transport, and the main characteristics of CO_2 streams for the purpose of storage. The amendments (Chapter 7) to the other Directives deal mainly with technical aspects of pipelines (Directive 85/337/EEC), licence management (Directive 2001/80/EC), and CO_2 streams composition (Directive 2008/1/EC).

The *Environmental Impact Assessment (EIA) Directive* (2011/92/EU as amended by 2014/52/EU) covers capture and transport of CO_2, considering that development projects in the EU must first be assessed for their impact on the environment before they can start.

The *Industrial Emissions Directive* (IED) aims to achieve a high level of protection of human health and the environment by reducing harmful industrial emissions across the EU. It is based on several pillars, including the need to have a permit for all kinds of industrial plants and the definition of the Best Available Techniques (BAT) to define emission limit values. The IED allows competent authorities some flexibility to set less strict emission limit values for specific cases but contains mandatory requirements on environmental inspections. Member States must set up a system of environmental inspections and draw up inspection plans accordingly.

The same regulation introduces the right of the public to participate in the decision-making process, and to be informed of its consequences, by having access to permit applications, permits and monitoring results. Emission data reported by Member States are made publicly accessible via the European Pollutant Release and Transfer Register (E-PRTR), which provides environmental information on all major industrial activities.

In 2022, the Commission adopted proposals to revise the IED and the E-PRTR. The proposals aim to improve the Directive by increasing the focus on energy, water, and material efficiency and reuse, thus providing a framework for the operation of EU industrial installations that is in line with the European Green Deal and the Zero-pollution action plan.

At the national level, the situation varies amongst the European countries. It should be noted, however, that a recent update of the state of national implementation of the CCS Directive, published in October 2023, shows that all European countries have transposed the Directive into national laws.

The report also indicates that: “since the third implementation report in 2019, considerable progress has been reported regarding the deployment of CO_2 storage sites notably but not only in the North Sea region in the form of awarded (or soon to be awarded) exploration permits, which are an important step towards a storage permit. EU Member States and Norway continue to support in the future, through their national programmes or funds, research and demonstration activities on CCS. Furthermore, many countries are involved in several European research and collaborative projects. The European Commission supports capture and storage of carbon dioxide with the ETS Innovation Fund, including full value chain projects combining capture, transport, and storage”.

Based on experience in other industries, the existence of a strong regulatory framework can play an important role in the creation of a favourable environment for industrial CCS development. The proposed method for Aurora can be based on the identification of these issues, also taking into consideration similar evaluations that have already been carried out (as, for example, in the CCUS Strategy project).

As such, a list of issues that contribute to the creation of a favourable environment, and thus represent KPI’s, could include:

1. CCUS integrated into national Carbon Neutrality strategies
2. Permitting and liabilities are clearly addressed in national legislation
3. Proper incentives for CO_2 capture, whether subsequently stored or used
4. Policies allowing trans-European CO_2 transport, use and storage.
5. Legal framework for CCUS infrastructure projects
6. Well-established and fast permitting process at national and local level for transport and storage infrastructures
7. CCUS integrated into Territory Special Planning tools
8. Existence of national strategy and a legal framework for hydrogen
9. Existence of a negative CO_2 emissions accounting framework (e.g., BECCS, DAC)
10. Incentives in the form of co-financing

CONCLUSION

The Aurora project will evaluate the full chain feasibility for two end user emitters in southern Europe. The methodology adopted for this analysis that will integrate the LCA performed for capture and transport steps, will allow to evaluate the best option for storage in southern Europe. The criteria and the approach is based on the previous results and classification adopted by Other EU project. The adopted methodology (in common with the most recent EU project) has the aims to be comparable as much as possible with the already performed evaluation of the other provinces/sites of Europe, with the aims to homogenise the results. This choice will favour standardization of the adopted criteria for site selection in European countries that still does not have a comprehensive storage atlas; on the other side, as this methodology includes some economical/commercial aspects, it will provide a more complete full chain analysis.

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