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Chapter 10

# Pre-Injection Phase: Site Selection and Characterization

B. Llamas, M. Arribas, E. Hernandez and
L.F. Mazadiego

Additional information is available at the end of the chapter

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## 1. Introduction

Depleted oil and gas fields, deep saline aquifers and non-mineable coal beds fulfil the special requirements for $CO_2$ storage and have become global references to develop this industry [2]. Depleted oil or gas fields have been well researched due to the associated industrial and economic value of these emplacements. While deep saline aquifers are among the most promising emplacements, since theoretically these structures offer the highest value in terms of capacity [2],[3], the risk associated with the exploration of these potential sites is greater than that for already investigated depleted oil or gas fields. In such cases, it is likely that multicriteria algorithms can facilitate evaluation to find the best option under consideration, so the results of this process will help the decision-maker to decrease the risk associated with the exploration of these potential emplacements.

The site selection phase comprises the identification, characterization and selection of emplacements that could be suitable for CCS among a list of candidates [4]. This phase is generally completed by the definition of the qualification criteria and the provision of the evidence concerning the reliable functioning of the emplacement according to these criteria. The selection of a suitable site also depends on the scale of the assessment. In this regard, every scale will be related to a different resolution and detail of information. It is possible to differentiate at least three levels, namely, basin level (identifying and quantifying large potential storage areas), regional level (increased level of detail, identifying areas to prospect) and local level (very detailed structures, pre-engineering site selection).

While the main mechanisms for $CO_2$ storage have been identified, and a series of criteria for site assessment and selection have been developed [5],[6],[7], a multicriteria algorithm to quantify and rank the potential areas under consideration has, to our knowledge, never been applied in an absolute mode, meaning that any alternative will be compared against a pattern.

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Thus, the objective of this study was to develop a methodology based on multicriteria algorithms for assessing the best emplacement for CCS within a range of alternatives.

In general, most of the areas which could be suitable for storing $CO_2$ are not well explored geologically. As a result, further exploration of the subsurface must be carried out, which implies higher cost and risks. In order to reduce the risk of failure, it is necessary to define a previous phase, which should be based on (1) data collection, and (2) the definition of a criterion and multicriteria decision tool.

The collection of data is independent of each country or region. It involves the study and processing of existing data, such as from geophysical surveys along with existing wells (shallow and deep) developed for oil and gas exploration, water resources and exploration, mining activities (exploration and extraction), exploration for nuclear waste deposits and underground natural gas storage activities. The data from these industrial activities can be complemented by other academic evaluations, including postgraduate theses and/or peer reviewed scientific articles.

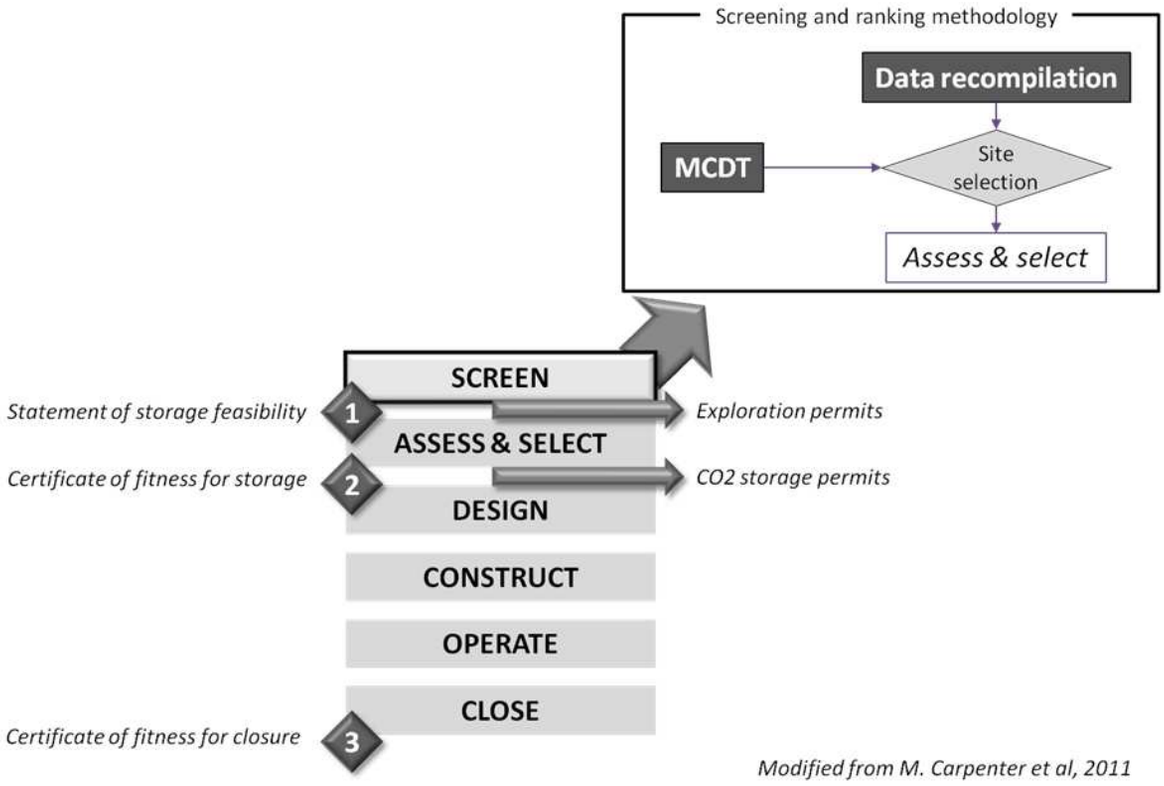



**Figure 1.** Work flow proposed for basin screening (Definition phase)

Figure 1 represents a proposed work flow [4]. The screening phase could be differentiated by the Data Recompilation task and the Multicriteria Decision Tool. It is integrated as a preliminary phase, and it is connected with a second phase called *characterization phase,* which corresponds to site maturation and testing.

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## 2. Site criteria definition

It is not only necessary to evaluate specific sites with a technical point of view. Sometimes problems can involve economic aspects or social acceptance, which could make a $CO_2$ storage site much more difficult (and costly). Therefore, it is necessary to establish a high level differentiation between technical and socioeconomic criteria (later we call this differentiation the 1st criteria level of the Analytical Hierarchy Process).

There is no standardization in this aspect, so the selection of the criteria should be as careful as possible, and should include all aspects that can make an area suitable or not. The criteria proposed in this chapter are based on the direct experience of the research group involved in this publication and on the evaluation of several publications and projects that focus on site selection methodology [10],[4].

Even though the criteria may be as described in the next sub-chapters, it is convenient to consider another type of classification, which is based on time scale and the possibility of modifying each criterion along that scale. Moreover, we can describe:

1. Geological, geothermal and hydrodynamic criteria are considered fixed, because they do not change, except in geological scale.
2. Knowledge of the basin is a criterion variable, because information can be increased over time.
3. Economic, political and social criteria are often variable because they change in a short time period.

### 2.1. Technical criteria

These criteria relate to scientific aspects or parameters to provide confidence in the findings about the subsurface structure. Deep subsurface exploration implies higher risk because the exploration techniques available are expensive and the probability of success is not high. In order to reduce the technical risk, it is necessary to define those criteria relevant for considering every critical issue.

**Tectonics.** This parameter comprises aspects like the structural definition of the trap at a basin and local level. The former considers whether the sedimentary basin is convergent or divergent, as well as its neotectonic activities. The latter relates to the type of the structure and trap, whether it is an anticline, syncline or seal fault [10]. Furthermore, the geo-mechanic evaluation should be taken into account in order to evaluate the maximum $CO_2$ injection pressure in the storage formation. This injectivity criterion defines the maximum capacity per unit of time.

**Geology.** This criterion evaluates the storage and the cap-rock formations. The common formations considered suitable for storing $CO_2$ are sandstones and limestones. These geological formations tend to have high porosity. While sandstone has a primary porosity, which is much more homogeneous, limestone presents secondary porosity, which is created by processes of diagenesis (e.g., leeching of minerals or the generation of a fracture system). Other

parameters to be defined in storage formations are permeability, and thickness of the formation. The plasticity, porosity and thickness of the cap-rock formations should also be evaluated and considered. In relation to the plasticity of the cap-rock formation, it is more desirable to have a ductile rather than a brittle behavior.

**Hydrogeology.** This parameter should consider both the dynamics and the fluid quality in the reservoir formation. Hydrodynamic criteria describe the natural dynamic flow system and hence the potential for hydrodynamic trapping within the basin under assessment. Shallow, short flow systems therefore do not meet the geological requirements for maintaining supercritical $CO_2$, in terms of depth, pressure and temperature, and do not have sufficient residence time to immobilize the injected $CO_2$ by one of the other trapping mechanisms, such as residual trapping, solution trapping or mineral trapping. Flow rate is controlled by the driving forces of the fluid, including its buoyancy and hydraulic gradient, and by the permeability and porosity characteristics of the reservoir rock through which the fluid is moving.

An additional sub-criterion that should be considered is the quality of the fluid under consideration. In this regard, it is mandatory to consider the principle of sustainability, whereby present actions cannot compromise future generations. Fluid quality is measured in Total Dissolved Solids (TDS), which define drinkable water (TDS < 3000 ppm). Thus, when drinkable water is present, the aquifer is not suitable for $CO_2$ storage. On the other hand, TDS higher than 10,000 ppm should be considered suitable for $CO_2$ storage operations, as the quality of this water makes it not suitable for any other activity.

**Subsurface conditions of the $CO_2$.** The most efficient way to store $CO_2$ underground is to store it under supercritical conditions, [2]. This special state of the $CO_2$ provides similar densities to a liquid (i.e., increasing the capacity per volumetric unit), while the viscosity is similar to a gas (i.e., increasing the capacity per unit of time). Supercritical conditions can be reached in $CO_2$ geology storage when the depth of the storage formation is higher than 800 m and the geothermal gradient is low (below 25 ∘C/km) [5,[6].

**Capacity.** The current methods for estimating $CO_2$ storage potential and capacity are based on widely accepted assumptions about geological trapping mechanisms, storage media and operating timeframes reviewed previously by other authors [2][6]. Using the concept of resources and reserves, the CSLF Task Force proposed a Techno-Economic Resource-Reserve Pyramid for $CO_2$ Storage Capacity, [11]. The various capacities are nested within the resource-reserves pyramid, and defined as Theoretical, Effective, Practical and Matched Storage Capacity.

This parameter is considered a technical criterion, but it is also relevant for economic reasons: it is necessary to define the $CO_2$ emitter in order to relate $CO_2$ emissions and capacity.

**Other geological formations.** $CO_2$ storage implies a long time period. Considering that the whole life cycle of the project includes characterization (pre-injection), injection, closure and post-closure as the most general phases, in addition to the storage itself, the project can last up to 100 years. Moreover, if there are any future modifications to the original conditions, such as mining activities or the development of oil fields, the confinement mechanisms may not be guaranteed. For this reason, it is necessary to consider every shallow geological formation that

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could be of potential use in the future. This will fulfill the sustainability principle previously described.

### 2.2. Socioeconomic criteria

These criteria include both economic aspects and parameters related to the social acceptance of the emplacement and its activity.

**The quantity and quality of the geological data,** although considered in many cases as an economic aspect, is one of the main criteria, as this information is used to determine and quantify the technical criteria referred to in the above text.

The more information is available, the fewer characterization methods will have to be applied. In this case, the characterization program (geophysics and wells) will be less expensive, and the risk of failure of the geological exploration will be reduced.

**$CO_2$ sources.** This criterion relates to the location details of the major stationary sources, and the distance between them and the areas of interest. An additional parameter to be considered is the flue gas quality ($CO_2$ quality). Certain gases ($NO_X$ or $SO_X$) can increase the interaction between the storage formation and the fluid injected [12]. These chemical interactions between injected gases and the storage or caprock formation materials can create precipitates or dissolutions, which can modify storage specifications of the area or structure.

**Regional location.** Whether an area or structure is onshore or offshore has an important economic consideration, since generally it is likely to be cheaper and technically easier to implement a $CO_2$ injection site onshore rather than offshore. On the other hand, public perception and land use issues may dictate that offshore sites are preferential for many $CO_2$ storage projects.

**Maturity of the Area.** This criterion considers those aspects which define, at a local level, the location of the areas under consideration. It includes key aspects such as the climate, existing infrastructure that may be affected by the geological exploration or $CO_2$ storage, and infrastructure that is required to develop the exploration program and engineering activities to develop the emplacement.

**Areas of interest: population, environmental and cultural resources.** This criterion refers to aspects that can affect acceptance of the emplacement by the community. Protest against the storage activity will be very demanding and obtaining legal approvals and permits may be delayed. For this reason, some special areas including major cities and those areas protected by the Natura 2000 network should not be considered as optimal areas for $CO_2$ storage. Furthermore, other areas with relevant monuments or archaeological sites should be taken into account in the model for assessing a potential emplacement.

## 3. Multicriteria decision making (MCDM)

Multiple criteria decision making (MCDM) is a methodology developed for making decisions in the presence of multiple, usually conflicting, criteria. Evaluation methods and multicriteria

decisions include the selection of a set of feasible alternatives, the simultaneous optimization of several objective functions, and a decision-making process and evaluation procedures that must be rational and consistent. The application of a mathematical model of decision-making will help to find the best solution, establishing the mechanisms to facilitate the management of information generated by the various disciplines of knowledge.

Those problems in which decision alternatives are finite are called Discrete Multicriteria Decision problems. Such problems are most common in reality and this case scenario will be applied in solving the problem of *site selection for storing* $CO_2$. Discrete MCDM is used to assess and decide on issues that by nature or design support a finite number of alternative solutions. Recently, Multicriteria Decision Analysis has been applied to hierarchy policy incentives for CCS [15] or to assess the role of CCS [16].

Assessment methods and criteria decision include selection among a set of feasible alternatives, optimization with various objective functions simultaneously, a decision-maker and rational and consistent procedures for assessment. Its principles are derived from matrix theory, graph theory, organizational theory, measurement theory, theory of collective decisions, operations research and economics.

The main evaluation methods are: linear weighting (scoring), multi-attribute utility (MAUT), overcoming relationships and hierarchical analysis (AHP).

Some of the advantages of AHP over other methods of Multicriteria Decision are:

1. It has a mathematical basis.
2. It enables breaking down and analyzing a problem in parts.
3. It allows measuring quantitative and qualitative criteria using a common scale.
4. It includes participation of different people or groups of interest to build consensus.
5. It enables checking the consistency index and making corrections, if applicable.
6. It generates a synthesis and provides the ability to perform sensitivity analyses.
7. It is easy to use and allows the solution to be complemented with mathematical optimization methods.

### 3.1. Analytical Hierarchy Process (AHP)

AHP is one of the most extensively used and powerful MCDM. Nowadays it is used by many companies in solving various multicriteria problems, ranking these in the following categories: selection, prioritization and assessment, provision of resources against a standard assessment, management and quality management and strategic planning. For example, AHP has been applied in the analysis of location, resource allocation, outsourcing, evaluation, manufacturing, marketing, supplier selection, finance, energy, education and risk analysis, [17]. This widespread use shows the suitability of AHP in solving various types of business decision-making problems.

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The AHP overcomes the problems with a scoring approach by structuring complexity as a hierarchy and by deriving ratio scale measures through pairwise relative comparisons. Pairwise comparisons are basic to the AHP method. Hence, when comparing a pair of criteria, sub-criteria or alternatives, a ratio of relative importance can be established. The pairwise comparison process can be performed using words, numbers, or graphical bars.

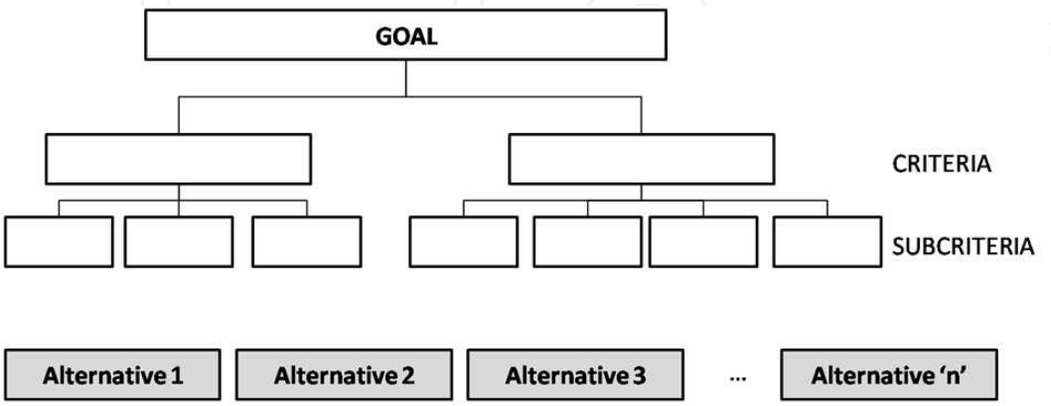



**Figure 2.** AHP Components: Four steps to build a hierarchy or network structure.

Once the model is built, pairwise comparisons are made with all individual elements (criteria, sub-criteria and alternatives). This process allows giving numerical values to the judgments provided by people, which is also able to measure how each element contributes to each level of the hierarchy. Furthermore, the process is based on a well-defined structure consisting of arrays, and the ability of the eigenvalues to generate values or to approximate weights of each criterion [18], [19], [20]. The problem of finding a nonzero solution to this set of equations is very common in engineering and physics and is known as an *eigenvalue problem.*

In order to carry out these comparisons, the AHP uses a fundamental scale of numbers that have proven absolute in practice and that have been experimentally validated for physical problems and decisions. This scale assigns mathematical values with respect to quantitative or qualitative attributes, homogenizing each valuable criterion.

Figure 4 illustrates the process followed for every criterion. As an example, Original Fluid Quality should be evaluated considering the Water Quality for different uses (agricultural sector, human use) and the European Directive for $CO_2$ storage; it is possible to establish different mathematical values for each measurable criterion.

### 3.2. Construction of the decision tree

As a major conclusion, a decision tree has been proposed. This model considers all the criteria described above, and they have been classified.

Weight assessment has been defined considering the AHP method: each level of the criteria and sub-criteria has been compared, using a comparison matrix, which should be constructed considering the consistency principle (it should fulfill the transitivity and reciprocity rules).

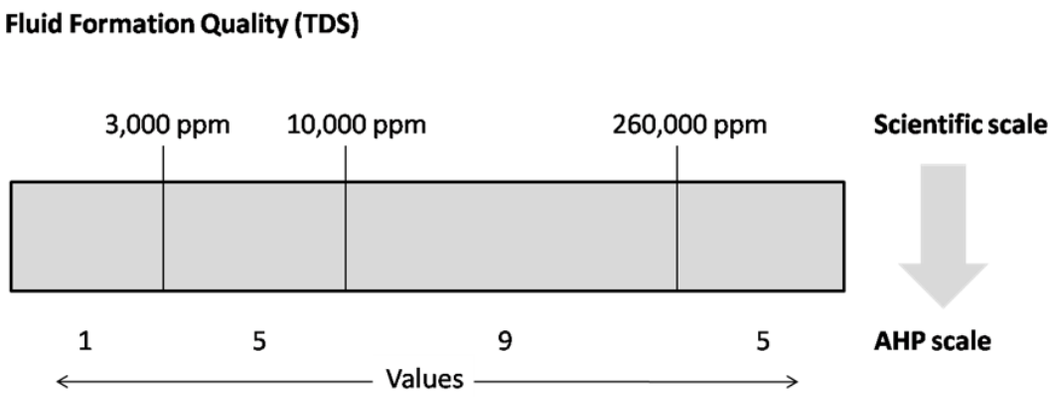



**Figure 3.** Scientific scale and translation into an AHP scale. This translation facilitates the evaluation of individual criteria (quantitative or qualitative) using a homogeneous scale.

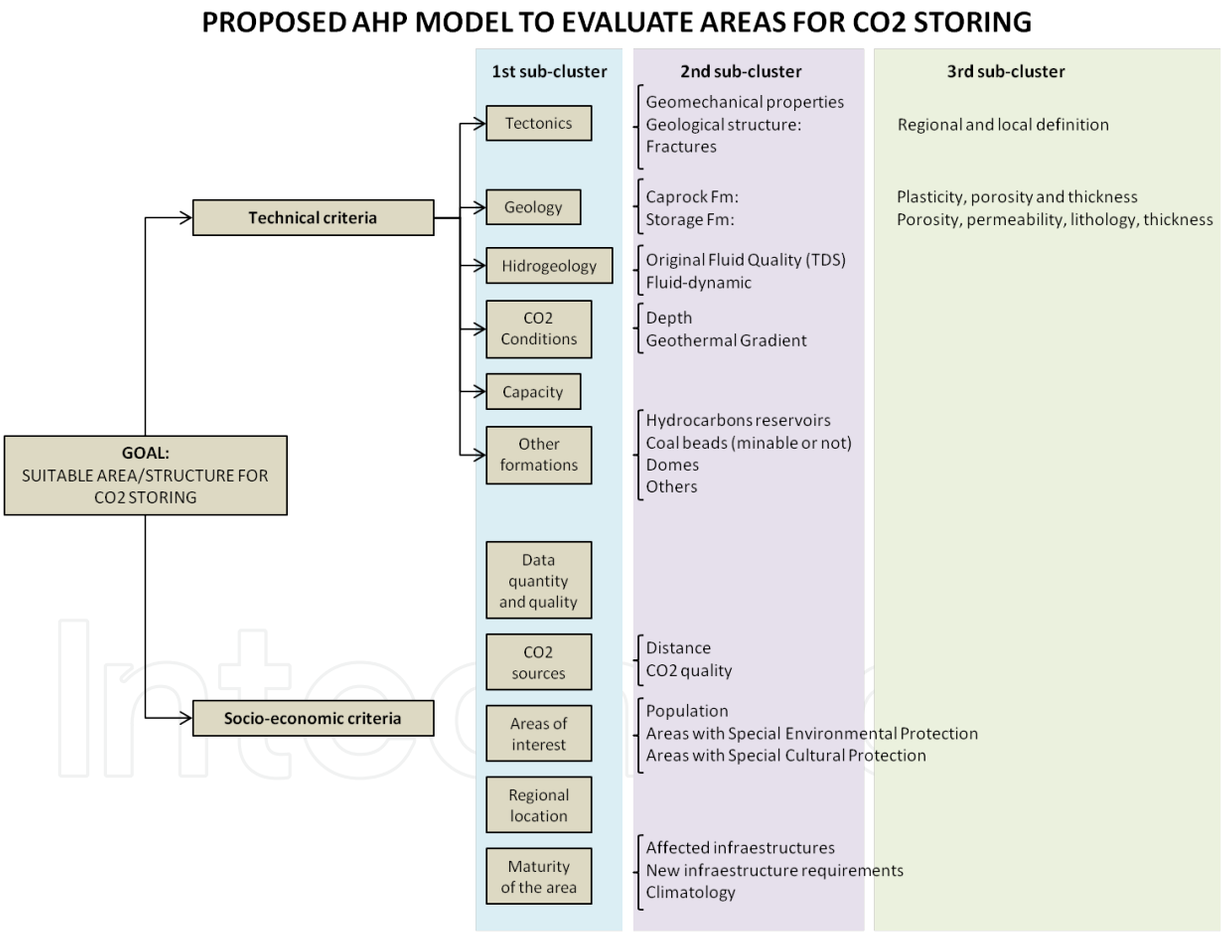



**Figure 4.** Analytical Hierarchy Process: criterion tree proposed to identify the best site for storing $CO_2$.

In order to "recover" or find the vector of weights, [w1, w2, w3,..., wn] given to these ratios, the matrix product of matrix A with the vector w can be calculated and considered in an equation, which is described as the eigenvalue matrix equation. The problem of obtaining a

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nonzero solution to this set of equations is very common in engineering and physics and is known as an eigenvalue problem.

$$[A]\cdot[W]=n\cdot[W]$$

Where *[A]* is the pairwise comparison matrix – where *n* Is the dimension – and *[W]* is the weight matrix (eigenvalues) for every criterion.

Site ($S_n$) assessment is evaluated using the formula:

$$S_n=\sum_{i=1}^{i=n} W_i\cdot V_i$$

Where $W_i$ are the weights of each criterion, and $V_i$ are the values assigned for the specific conditions of each site.

AHP as an absolute mode

AHP is a multicriteria methodology which has been developed for use in two different ways: relative and absolute mode. In the first case, all the alternatives are compared between each other, but no more than seven alternatives are recommended for evaluation at the same time.

There are two reasons to justify this limitation: (1) consistency principle and (2) neurons. Pairwise comparisons errors increase due to inconsistent judgments. It is possible to distribute this inconsistency among all the alternatives under evaluation. If the number of alternatives/elements is low, the priorities will be less affected by this inconsistency. The neuronal explanation has its limits in the brain's ability to identify simultaneous events: the more criteria exist for pairwise comparison, the greater the risk of inconsistent judgments will be.

For this study, we consider the AHP algorithm in absolute mode. It requires a standard with which to compare alternatives. The process leads to absolute preservation in the rank of the alternatives no matter how many are introduced. In this case, it is possible to define a standard considering the best values for each criterion (see Table 1and Table 2).

| **Tectonic, structural** | | | | **Hydrogeology** | | |
|---|---|---|---|---|---|---|
| Geo mechanical | Lateral continuity | Fractures | | TDS | Hydro-dynamic | |
| Stable domain | Anticline | Weakly fractured. Few faults | | > 10.000 | Regional | |
| **Storage** | | | | **Caprock** | | |
| Porosity (%) | Permeability | Thickness (m) | Lithology | Plasticity | Thickness (m) | Porosity |
| >25 | > 1 D | >100 | Sandstone | Ductile | > 100 | < 5 |
| **CO2 conditions** | | **Capacity (Mt CO2)** | **Other formations** | | | |
| **Deep (m)** | **Temperature** | | **Oil or gas** | **Coal beds** | **Massive saline** | **Other** |
| >1.000 years | 900~2.000 | > 150 | Yes, huge volume | Yes; deep 200~800m | Beds | Exploitation permits |

**Table 1.** Technical criteria and their best values for $CO_2$ storage alternatives.

| $CO_2$ source | | | | | | | | Maturity | |
|---|---|---|---|---|---|---|---|---|---|
| Quality of the information | Distance (km) | $CO_2$ Quality | Population (km) | Environmental resources (km) | Cultural resources (km) | Location | Climatology | Affected Infrastructure | New infrastructure |
| Detail data (GIS) based on deep data (wells and seismic) | < 25 | Impurity content less than 1% | >50 | >20 | >20 | Onshore | Moderate | All | None |

**Table 2.** Socio-economical criteria and its best values for $CO_2$ storage alternative.

## 4. CO2SITE ASSESS: Informatics tool

As described before, site selection is based on several criteria, values and weights. Even though the methodology proposed in this chapter allows selecting the best option in a quantitative and objective way, it is necessary to consider other points of view of the problem. Indeed, $CO_2$ storage is a controversial way to remove $CO_2$ from the atmosphere and even though it has been described a safe and affordable, there are many stakeholders who consider it unreliable.

For those reason, and to manage the huge amount of technical information and different weight definitions of each criterion, a specific program has been developed: CO2SITE ASSESS. This software has been developed in VISUAL BASIC© (easy in terms of programming and speed in obtaining results, robust integration with Data Base, allowing operations in read/write formats). It includes the AHP algorithm (weights and values), so its interaction with the end-user is easy. Many of the technical and socioeconomic parameters can be represented in a Geographical Information System (GIS), so the CO2SITEASSESS results also generate a file which allows representing the results and *$CO_2$ site storage assessment*.

It is possible to differentiate two different databases: the first one comprises the $CO_2$ emitters and its data (location, $CO_2$ emission, primary energy, date of commissioning, and others), whereas the second database includes the $CO_2$ storage location. Data to be included in this form should be the technical and socioeconomic criteria previously described, and the tool can compare the alternatives using the AHP algorithm and decision tree described in this chapter.

The results classify each area into five levels: optimal, good, normal, poor and very poor. These values will help decision makers to evaluate which areas are the best considered and if it is reliable to go to the next stage.

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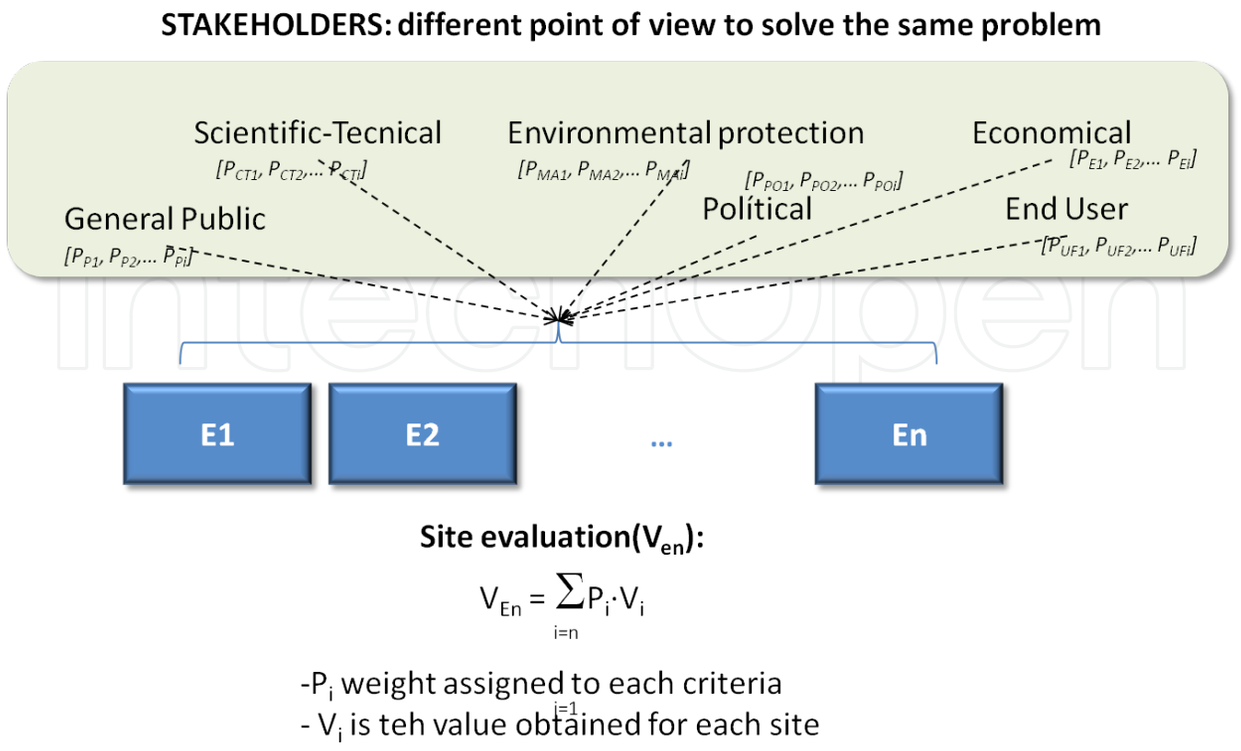



**Figure 5.** CO2 storage site selection. A complex issue with different stakeholders

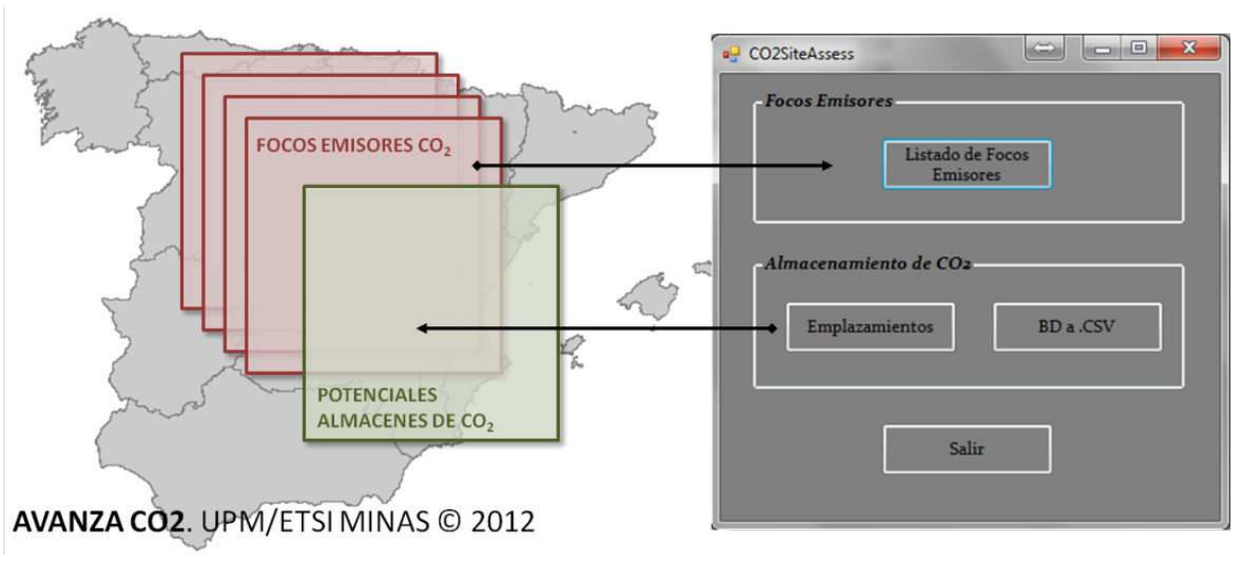



**Figure 6.** CO2SITEASSES is a program to evaluate multiple criteria and to obtain georeferenced information related to potential $CO_2$ store areas.

This tool is useful to compare many structures – even if there are many alternatives – and since the algorithm implemented in its code is based on AHP absolute mode, it is possible to compare more than seven alternatives.

## 5. Site selection: Evaluation of different options in southern Spain

According to the Description of Work of the AVANZA CO2 project (national project supported by the Ministry of Industry and Tourism), the methodology proposed in this chapter has been applied to study specific geological structures. The company that supports this study (SACYR) considers bio-CCS technology as an option to decrease the $CO_2$ emissions from its biomass plants located in the Guadalquivir basin (South of Spain). This study was carried out by the Technical University of Madrid, in collaboration with Gessal.

Guadalquivir basin: an area of potential interest

The Guadalquivir basin in southern Spain is an ENE–WSW elongated foreland basin developed during the Neogene and Quaternary between the external zones of the Betic Cordillera to the south and Sierra Morena (Iberian Massif) to the north [24], which respectively forms its active and passive margins. The external zones of the Betic Foldchain are made up of Mesozoic and Cenozoic sediments that include thick calcareous and evaporitic formations, as well as siliciclastic units.

Sediments of the basin can be divided into two main stratigraphic: the lower, which includes materials deposited prior to the collision and embodies a long sedimentary process ranging from Cambrian to Permian, culminating in a strong tectonic collision known as the Hercynian orogeny; and the upper, comprising materials of the foreland basin itself, which is known as the alpine stage and begins with an intensive erosional period (Hercynian discordance), and a new subsequent sedimentary period that spreads from Upper Permian to Quaternary. The latter constitutes the proper filling of the foreland basin. It can be divided into five depositional sequences (relatively consistent set of strata, genetically related and whose roof and wall are discontinuity or continuity sequences).

It is possible to individualize two main sub-stages, which are disconnected by the alpine tectonic stage, of Burdigalian age. These sub-stages are:

1. From Permian to Lower Miocene, sedimentation takes place over a passive or Atlantic type margin, which differentiates - from North to South- platform, talus and deep water facies. These paleogeographic realms are known as Prebetic, Intermediate Unit, Subbetic and Flysch.
2. The Alpine orogeny reached its main deformation phase during the lower Miocene. We interpret this phase under a classical deformation model –intra continent subduction type, taking place under NW-SE and E-W compressional vectors.

In the same way as many other alpine forelands, compressive deformation seems to have been established by following a classic model of piggy back or progressive tectonic propagation, from the early active Southern System's Front to the Northern Passive Margin.

The selection of this area was made according to the following information:

1. The interest in the Guadalquivir Basin as a potential area for storing $CO_2$ has been described in national and European Projects.

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2. Technical conditions: Some structures were described in the Geocapacity Project, and others were proposed under the AVANZA CO2 Project.

3. Economic conditions: The specific area of interest is also defined due the interest of the company SACYR. This company has some power stations which use biomass as primary energy near this location. The interest of the company was evaluated in this area to develop the bio-CCS concept.

| Structure | Associated wells |
|---|---|
| **A** | Fuensanta 1 |
| **B** | R. Guadalquivir H-1 |
| **C** | Nueva Carteya-1 |
| **D** | R. Guadalquivir K-1 |
| **Córdoba E** | Baeza 1, 2, 3 and Bailen 1 |
| **Córdoba S** | Guadalquivir N-1 |

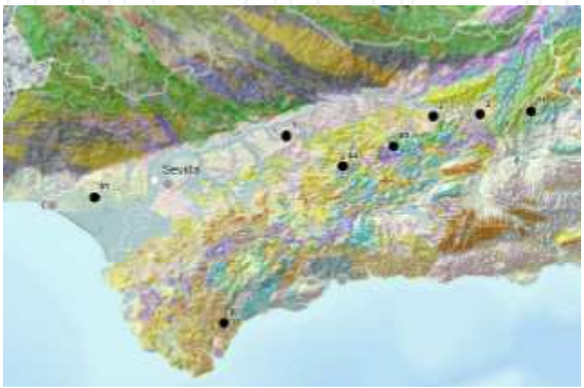



**Figure 7.** Detail of selected structures, and figures taken from previous studies by the IGME (Geocapacity project).

According to previous stratigraphic, petrological and petrophysical data obtained from exploration wells, it is possible to define preferred targets; both caprock and storage formations. The data include seismic reflection and refraction profiles, well logs, gravity and field observations.

Finally, structural definition was done based on the interpretation of the geophysical data in each area. These interpretations allow us to define specific structures and define the $CO_2$ capacity of each structure. Well interpretation was used to identify storage and caprock properties.

### 5.1. Sites evaluation: Application of the AHP model to this area

Some of the structures considered were not evaluated for different conditions (shallow storage formations, lack of data or low thickness of the storage formations). These conditions should not eliminate these structures – indeed they have been included in the CO2SITEASSESS data base – but social or economic aspects will cause them to be considered the worst areas to develop $CO_2$ storage.

For instance, A, B and C are the alternatives that have been considered. Even if the capacity calculated for each area is not enough for an industrial scale project, it could be considered for a pilot project or demonstration of the bio-CCS technology in Spain.

Moreover, CO2SITEASSESS was used in another region (Duero Basin, also in Spain), where the assessment of this structures are much better than in the Guadalquivir basin.

| ID | BASIN | | VALUE | NOTE |
|---|---|---|---|---|
| 1 | Duero | El Gredal-Utrillas | **1** | **POOR** |
| 2 | Duero | El Gredal-Bunt | 7.26 | GOOD |
| 3 | Guadalquivir | Fuensanta de Martos | **1** | **POOR** |
| 4 | Guadalquivir | Guadalquivir H1 | 6.33 | NORMAL |
| 5 | Guadalquivir | Nueva Carteya | 6.54 | NORMAL |

**Table 3.** CO2SITEASSESS results.

All the areas defined in the present chapter have been previously defined by several hydrocarbon explorations: geophysical surveys and wells were considered: more than 10 wells were evaluated and hundreds of seismic studies were evaluated. Indeed, this region has active natural gas reservoirs – in two different turbidite systems: the Arenas del Guadiana Fm. in the Poseidón Gas field, in the Gulf of Cadiz, and the Arenas del Guadalquivir Fm., which produces from several small fields that are located onshore, in the Guadalquivir basin.

Moreover, outcrops were analyzed to properly evaluate mineral composition, hydrogeology and maturity conditions.

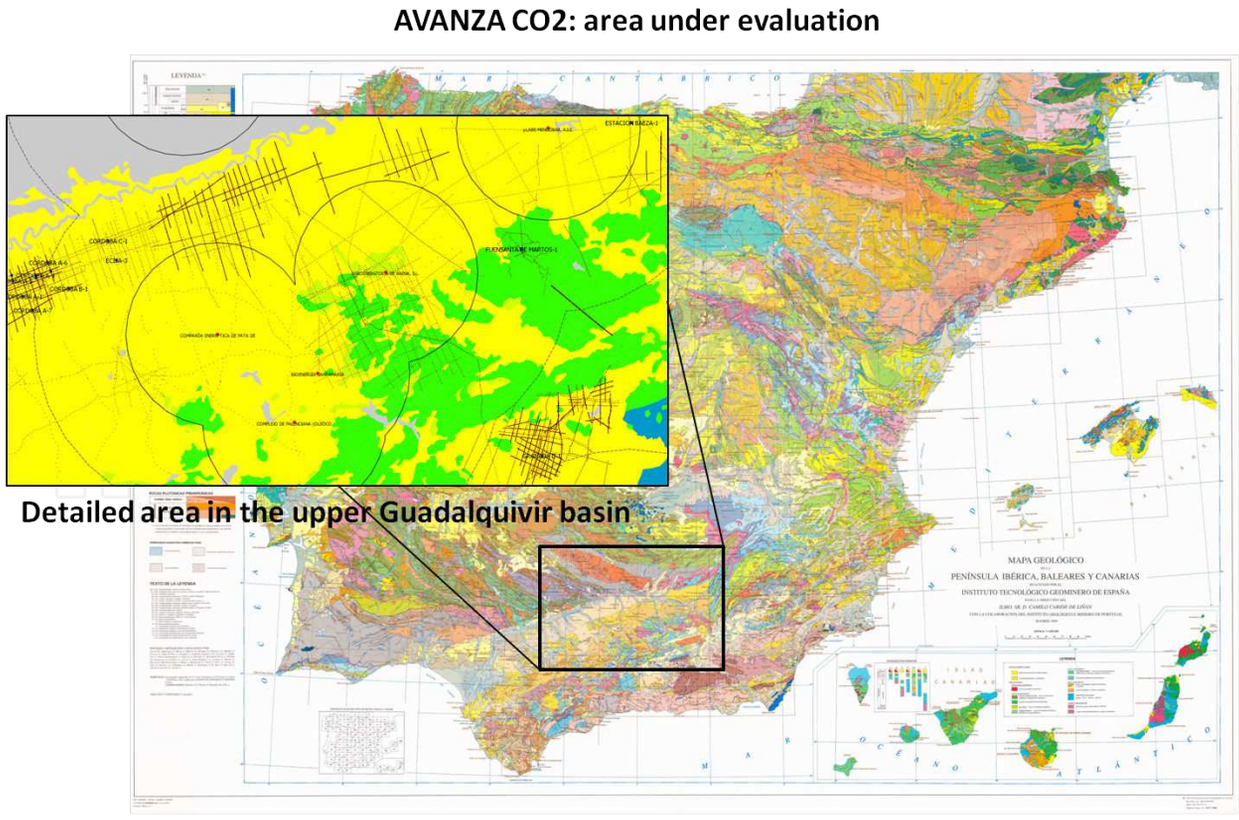



**Figure 8.** Spanish geological map and detailed area under evaluation. Source: IGME and AVANZA CO2 project.

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**FUENSANTA (Alternative A):** Located in the basin's internal prebetic area (intermediate unit). As reservoir this study evaluated a carbonate rock belonging to Dogger – Lias, whereas a marls is considered as the caprock.

The anticlinal trap, from the data collected, is estimated to have a total area of 15 km$^2$ of Structure A. The roof of the structure would be located at 1081 m.

Existence of water with low salt content has been confirmed (7 gr/l). Structure-Trap Anticline, elongated in EW direction, preserved under Subbetic materials in its western part, limited by a front thrust in its margin N, N-verging. structural closure to the "spill point" is around 400 milliseconds, which may involve around 700-800 meters.

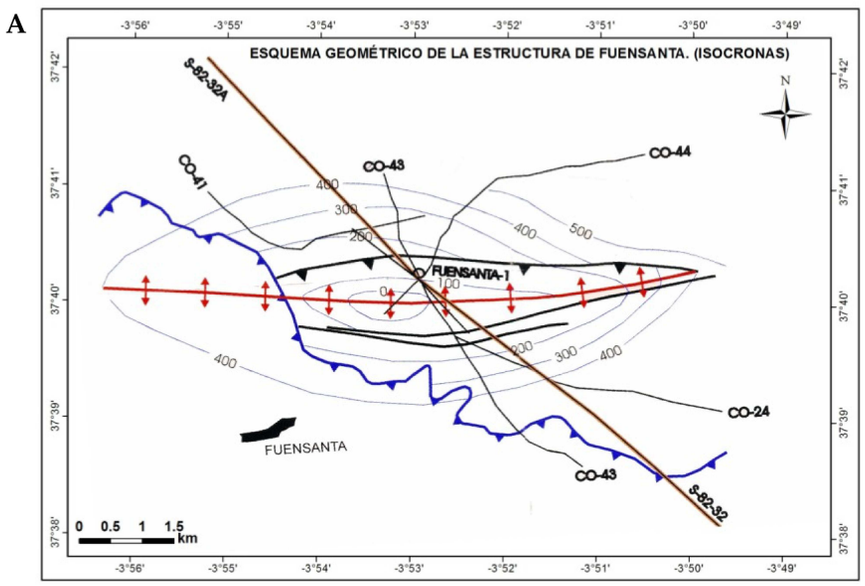



**Figure 9.** Detailed description of the *Fuensanta structure* (called alternative A)

**GUADALQUIVIR H-1 (Alternative B):** Located within the basin internal prebetic. It is possible to define As Dogger oolitic carbonates as a storage reservoir, whereas the Malm marl may be considered as its caprock.

The trap is defined as a folding anticlinal; considering the data collected it is estimated to have a total area of 26 km$^2$. The roof of the store formation would be located at 1668 m. However, the target (corresponding to the Oolític Dogger *Jabalcuz* formation) has low porosity, between 2.25 and 4%.

For instance, it is possible to define a potential reservoir and a caprock.

| | Level | I | II | III | IV | V |
|---|---|---|---|---|---|---|
| | Criteria | | | | | |
| | (math) VALUE | 1 | 3 | 5 | 7 | 9 |
| Tectonic, structural | Geo mechanical | | Unstable domain | | Stable domain | |
| | Lateral continuity | Convergent Basins. Volcanic Activity | Convergent Basins. Neo tectonics | | Divergent Basins. | |
| | | | Syncline | | Horizontal or sub horizontal | Anticline |
| | Fractures | | Strongly fractured. Many faults | | Weakly fractured. Few faults | |
| Storage | Porosity (%) | < 10 (5.0) | | 10~25 | | >25 |
| | Permeability | < 1 mD | | 1~100 mD (10-10^2) | | > 1 D |
| | Thickness (m) | | < 10 | 10~100 | | >100 (175 m.) |
| | Lithology | | Other | | Carbonates | Sandstone |
| Caprock | Plasticity | Fragile | | Intermediate | | Ductile |
| | Thickness (m) | < 10 | | Active region 10~100 | Stable region 10~100 | > 100 (173 m.) |
| | Porosity | > 10 | | 10 ~ 5 | | < 5 |
| Hydrogeology | TDS | < 3 000 | | 3 000~10 000 >260 000 | | > 10 000 |
| | Hydro-dynamic | Local < 100 years | | Area 100~1000 years | | Regional >1 000 years |
| | Deep (m) | < 600 | | 600~900 | > 2 000 | 900~2 000 |
| | Temperature | | Warm basin | Mild temperate basin | Cold basin | |
| | Capacity ($Mt\ CO_2$) | < 10 | 10~50 | 50~100 | 100~150 | > 150 |
| Otras formaciones | Oil or gas | | NO | Yes, small volume | Yes. Medium volume | Yes, huge volume |
| | Coal beds | | NO | Yes. No methane presence | Yes; deep > 800m | Yes; deep 200~800m |
| | Massive saline | | NO | Domes | Beds | |
| | Other | Exploration | | Evidence. Exploration or research permits | | Explotation permits |

**Figure 10.** Evaluation of alternative A, using the AHP model described above.

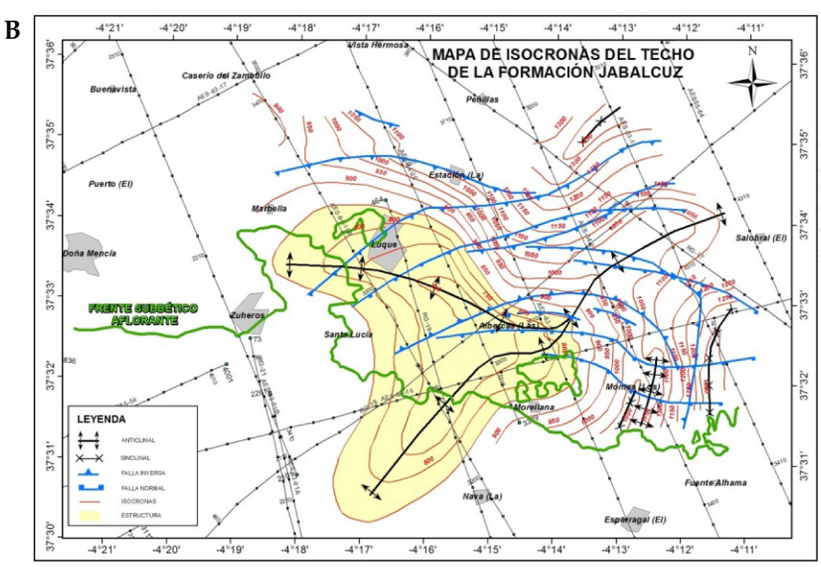



**Figure 11.** Detailed description of the *Guadalquivir H-1 structure* (called alternative B)

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| | Level | I | II | III | IV | V |
|---|---|---|---|---|---|---|
| | Criteria | | | | | |
| | (math) VALUE | 1 | 3 | 5 | 7 | 9 |
| Tectonic, structural | Geo mechanical | | Unstable domain | | Stable domain | |
| | Lateral continuity | Convergent Basins. Volcanic Activity | Convergent Basins. Neo tectonics | | Divergent Basins. | |
| | | | Syncline | | Horizontal or sub horizontal | Anticline |
| | Fractures | | Strongly fractured. Many faults | | Weakly fractured. Few faults | |
| Storage | Porosity (%) | < 10 (4) | | 10~25 | | >25 |
| | Permeability | < 1 mD | | 1~100 mD | | > 1 D |
| | Thickness (m) | | < 10 | 10~100 (84) | | >100 |
| | Lithology | | Other | | Carbonates | Sandstone |
| Caprock | Plasticity | Fragile | | Intermediate | marls | Ductile |
| | Thickness (m) | < 10 | | Active region 10~100 | Stable region 10~100 | > 100 (140) |
| | Porosity | > 10 | | 10 ~ 5 | | < 5 |
| Hydrogeology | TDS | < 3 000 | | 3 000~10 000 >260 000 | | > 10 000 (no documentado) |
| | Hydro-dynamic | Local < 100 years | | Area 100~1000 years | | Regional >1 000 years |
| | Deep (m) | < 600 | | 600~900 | > 2 000 | 900~2 000 |
| | Temperature | | Warm basin | Mild temperate basin | Cold basin | |
| | Capacity ($Mt\ CO_2$) | < 10 | 10~50 | 50~100 | 100~150 | > 150 |
| Otras formaciones | Oil or gas | | NO | Yes, small volume | Yes. Medium volume | Yes, huge volume |
| | Coal beds | | NO | Yes. No methane presence | Yes; deep > 800m | Yes; deep 200~800m |
| | Massive saline | | NO | Domes | Beds | |
| | Other | Exploration | | Evidence. Exploration or research permits | | Explotation permits |

**Figure 12.** Evaluation of alternative B, using the AHP model described above.

**NUEVA CARTEYA - 1.** Within the pre-betic terminal basin, the carbonate reservoir rock (Dogger oolitic) was evaluated. Malm marls are considered to be caprock.

The trap is an anticline, with a total area of 30 $km^2$ and estimated thickness of 160 m. The roof would be located at a depth of 1240 m.

Although a storage formation has been defined, it is necessary to study whether this structure is closed.

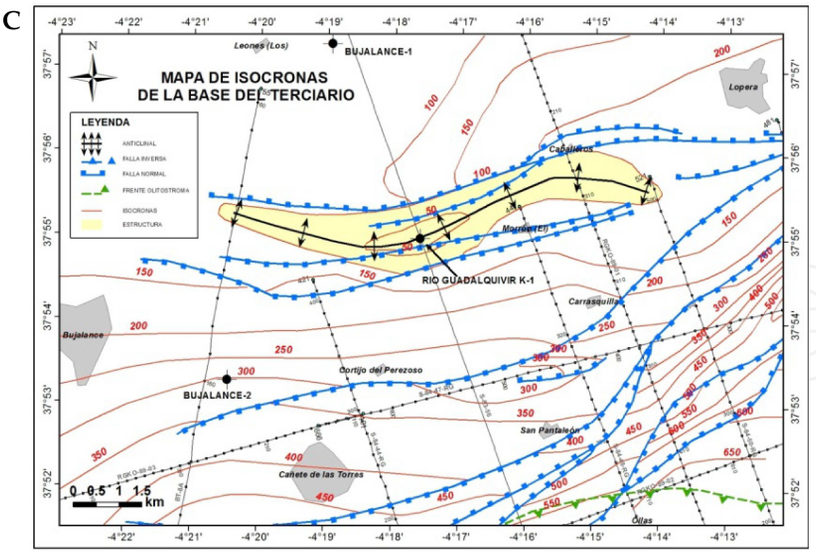



**Figure 13.** Detailed description of the *Guadalquivir H-1 structure* (called alternative C)

| | Level / Criteria | I | II | III | IV | V |
|---|---|---|---|---|---|---|
| | (math) VALUE | 1 | 3 | 5 | 7 | 9 |
| Tectonic, structural | Geo mechanical | | Unstable domain | | Stable domain | |
| | Lateral continuity | Convergent Basins. Volcanic Activity | Convergent Basins. Neo tectonics | | Divergent Basins. | |
| | | | Syncline | | Horizontal or sub horizontal | Anticline |
| | Fractures | | Strongly fractured. Many faults | | Weakly fractured. Few faults | |
| Storage | Porosity (%) | < 10 (3.0) | | 10~25 | | >25 |
| | Permeability | < 1 mD | | 1~100 mD | | > 1 D |
| | Thickness (m) | | < 10 | 10~100 | | >100 (160) |
| | Lithology | | Other | | Carbonates | Sandstone |
| Caprock | Plasticity | Fragile | | Intermediate | | Ductile |
| | Thickness (m) | < 10 | | Active region 10~100 (50) | Stable region 10~100 | > 100 |
| | Porosity | > 10 | | 10 ~ 5 | | < 5 |
| Hydrogeology | TDS | < 3 000 | | 3 000~10 000 >260 000 | | > 10 000 190 gr/L |
| | Hydro-dynamic | Local < 100 years | | Area 100~1000 years | | Regional >1 000 years |
| | Deep (m) | < 600 | | 600~900 | > 2 000 | 900~2 000 (1220 a 1380 m) |
| | Temperature | | Warm basin | Mild temperate basin | Cold basin | |
| | Capacity ($Mt\ CO_2$) | < 10 | 10~50 | 50~100 | 100~150 | > 150 |
| Otras formaciones | Oil or gas | | NO | Yes, small volume | Yes. Medium volume | Yes, huge volume |
| | Coal beds | | NO | Yes. No methane presence | Yes; deep > 800m | Yes; deep 200~800m |
| | Massive saline | | NO | Domes | Beds | |
| | Other | Exploration | | Evidence. Exploration or research permits | | Explotation permits |

**Figure 14.** Evaluation of alternative C, using the AHP model described above.

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### 5.2. Socioeconomic values

The area under evaluation contains different features in the same region. For instance, while the socioeconomic parameters can be considered similar for all of them, other parameters are different slightly different (i.e., distance from $CO_2$ sources, storage area and the nearest town). It was possible to estimate the values marked in the Figure 15.

| | Class / Criteria | I | II | III | IV | V |
|---|---|---|---|---|---|---|
| | (math) VALUE | 1 | 3 | 5 | 7 | 9 |
| | Quality of the information | No data. It isn't possible to make any geological interpretation | Few data. It's possible to make an interpretation based on adjacent regions | Detail data and enough deep. General or shallow data. | Digital regional data (GIS). | Detail data (GIS) based on deep data (well and seismic data) |
| | Distance (km) | > 250 | 250´´100 | 100´´50 | 50´´25 | < 25 |
| | $CO_2$ Quality | Impurity content up to 2% | | Impurity content between 1-2% | | Impurity content less than 1% |
| | Population (km) | < 10 | 10´´25 Unfavorable topography | 10´´25 Favorable topography | 25´´50 | >50 |
| | Environmental resources (km) | 0 | | 10´´20 | | >20 |
| | Cultural resources (km) | 0 | | 10´´20 | | >20 |
| | Location | | Offshore (deep) | Offshore (shallow) | Onshore | |
| Maturity | Climatology | | Extreme | | Warm | |
| Maturity | Affected Infrastructure | | None | Little | | All |
| Maturity | New infrastruture | | All | Little | | None |

**Figure 15.** Evaluation of socioeconomic parameters

The area was explored during the twentieth century, so there is enough information to build a GIS and to define some of the structures (conceptual or static model). As shown in Figure 8, there are industrial $CO_2$ sources a short distance away and the quality of the flue gases is sufficient. Some of the emitters are biomass power stations, but close to this region it might be possible to identify a larger emitter (Puente Nuevo power plant, close to Córdoba).

There are towns and cities close to each structure, but the topography can be considered favorable, and there are no environmentally protected areas close to the structures under evaluation.

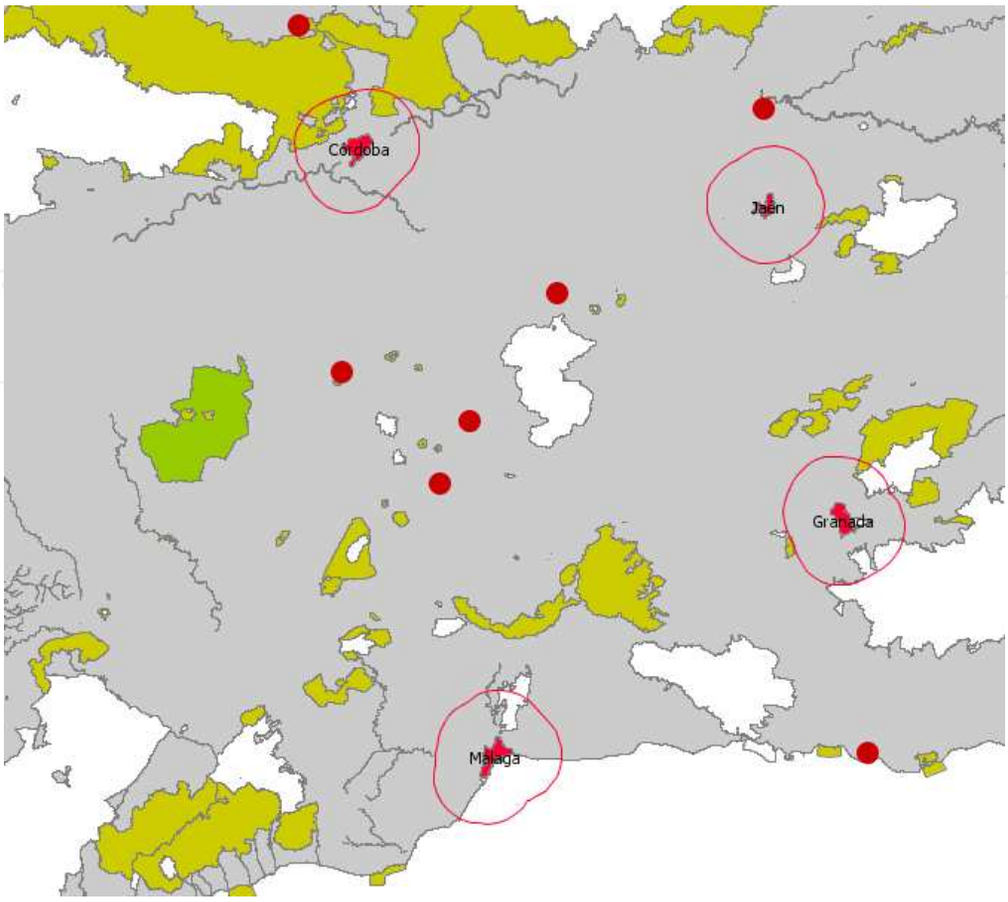



**Figure 16.** Protected areas (environmental conditions: white and green areas), and towns (red dots) in the area of interest.

## 6. Conclusions

Site selection for storing $CO_2$ is a complex issue, especially when deep saline aquifers are under assessment. These geological structures used to be poorly characterized and the risk of unsuccessful geology exploration is high. For this reason, the Multicriteria Decision Tool can be used to evaluate related technical and socioeconomic data on different alternatives under consideration. In addition, there are different stakeholders with different points of view, so the decision maker needs to take these viewpoints into account.

AHP is the proposed multicriteria algorithm. It selects the best area in an objective way. Therefore, its use decreases the risk associated with the site selection phase, and it will easily show the strengths and weaknesses of the information or characteristics of the alternatives under study. Furthermore, it can help increase social acceptance by stakeholders.

An innovative program (CO2SITEASSESS) was been developed and validated, using some defined areas (at basin and regional scale) and structures (local scale). This software also allows obtaining georeferenced data; and the combination of both uses (georeferenced data and AHP

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algorithm) has never before been applied to select areas to store $CO_2$. This combination has some advantages:

1. The results are obtained using a decision tree and multicriteria algorithm (Analytical Hierarchy Processes).
2. The results are objective – all the alternatives are compared with a defined standard (absolute measurements).
3. The results can be represented in a GIS, so the data can be referenced on a map, helping to make decisions.
4. This software easily allows different evaluations – considering different stakeholders with different points of view.
5. It saves a lot of time in decision-making, and generates a range of information useful for taking decisions.

In addition, some of the criteria can change during the pre-injection phase (i.e., data available, other formations of interest, etc.) and this tool can be useful to consider at which stage each alternative is during a period of time (pre-injection: selection, characterization, static or dynamic model and engineering).

The results obtained in the High Guadalquivir basin suggest that this area is not suitable for $CO_2$ storage on an industrial scale, but some of the structures considered in this chapter could be useful for pilot scale, especially if bio-CCS technology is applied.

Nevertheless, the CO2SITEASSES methodology has been demonstrated as robust to identify the best alternative under evaluation, and it reduces the inherent risk associated with geological explorations.

The AHP is applied in this study in an absolute mode, so it allows the assessment of limitless alternatives. For instance, this method and software can be useful as a standard in different regions (i.e., Spain or Europe).

Another version of the CO2SITEASSESS will be developed in the near future to relate site selection and a program characterization of each alternative. This characterization program will consider the three characterization phases: outcrop, geophysics and wells.

## Author details

B. Llamas[1*], M. Arribas[1], E. Hernandez[2] and L.F. Mazadiego[1]

*Address all correspondence to: bernardo.llamas@upm.es

1 Technical University of Madrid. Engineering School of Mines, Madrid, Spain

2 GESSAL, Madrid, Spain

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