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AHP algorithm used to select suitable abandoned underground mines for energy storage infrastructure – iCAES technology. A specific case study for León (Spain)

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ABSTRACT

In the energy transition, the promotion of renewable sources entails the development of storage technologies to manage the mismatch between energy production and demand. In this scenario, the use of CAES (Compressed Air Energy Storage) technology enables the efficient and cost-effective storage of large amounts of energy. However, this technology is developed in salt domes who have an inherent risk associated of underground exploration phase. To address this, we propose to develop an infrastructure (iCAES) in abandoned underground mines, where the exploration phase is completed and well known. For its implementation, this paper defines a structure hierarchization method gathers the technical and socio-economic criteria. It involves a multi-criteria problem, and the correct selection of the location must be based on specific mathematical algorithms. For this case the Analytic Hierarchy Process (AHP) from multi-criteria decision making (MCDM) methods allows quantified by means of a scientific and mathematical scale and the assignment of weights, so that it is possible to evaluate different alternatives. This is possible thanks to the application of the AHP model in absolute terms. The information gathering has been based on the specific case study of coal basins in the north of Spain, in the region of León. Considering the proposed methodology, the most suitable alternative locations to implement iCAES in the region of León were identified.

1. Introduction

The energy transition towards a sustainable model committed by the Organization for Economic Co-operation and Development (OECD) that ratified the Paris Agreement [1] should bring environmental benefits. The universal agreement's main aim is to keep a global temperature rise this century well below 2 °C and to drive efforts to limit the temperature increase even further to 1.5 °C above pre-industrial levels [2]. Especially in the current complex geopolitical context, energy sources must be indigenous.

The drastic decrease in the use of fossil fuels in electricity generation in Europe [3] did not have a similar effect on the concentration of CO_2 in the atmosphere: the Mauna Loa station [4] records a concentration above 415 ppm. But the most worrying thing is the

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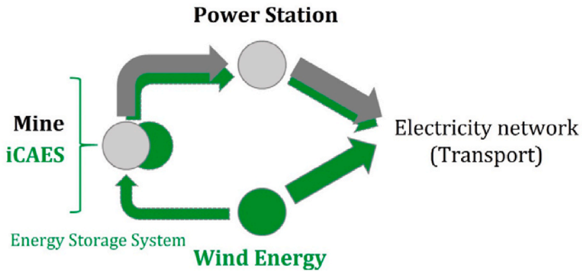

Fig. 1. iCAES technology as a circular economy technology: re-using abandoned coal mines.

concentration's growth rate, whose average values reached 2.5 ppm/year in the last decade. According to the latest report published by the International Energy Agency [5], fossil fuels supplied 80.9% of the energy consumed. Oil and coal are the most significant ones.

Unfortunately, the transition to a sustainable energy model is not a simple matter when it comes to the selection of technologies [6], since each technology has advantages and disadvantages regarding the analysis of the Energy Trilemma [7]: security of supply, environmental impact, and competitiveness. The European Commission has opted for restrictive policies [8] regarding CO_2 emissions in industrial sectors included in the EU Emission Trading System (ETS). After the implementation of its fourth phase, the average cost of emission allowances in 2021 amounted to 53.55 €/tCO_2 [9]. In this way, a decarbonization policy [10] and the promotion of renewable sources (wind and photo-voltaic) [11,12] is fostered by means of the double objective of archiving energy independence and the reduction of environmental impact.

However, wind and photovoltaic renewable sources have a low load factor, as they depend on intermittent energy sources (wind and solar radiation) with a strong impact on the security of supply. In order to increase flexibility between generation and demand, these technologies require energy storage techniques for their massive deployment in the electricity generation mix [13].

There are different scales of energy storage [14,15] and reversible water pumping stands out with 96.44% of the energy storage capacity [16]. Other mechanical energy sources are also established as mature technology, like underground compressed air storage (CAES), which is a technically viable alternative. In order to increase its competitiveness, it is necessary for the compression system to have an energy storage system or thermal energy management [17–19], so that it becomes an adiabatic system [20].

However, exploring subsurface storage systems is risky [21] and is subject to a high cost derived from researching and operating an infrastructure at depths greater than 700 m, such as those currently in operation in Huntorf and McIntosh [22,23]. This is why research in shallower and smaller cavities has come up with concepts based on lower CAES [24,25].

This paper considers other subsurface storage options, like the use of obsolete infrastructures, such as galleries in abandoned mines [26,27], since the disuse of coal mines in Europe has an impact in economic and social terms [28].

Currently, most subterranean infrastructures are abandoned without further use [29,30], but they could be reused to promote circular economy for a current and necessary purpose. This would contribute to achieving several sustainable development goals [31] and introducing circular economy in the mining sector, given the fact that it is still in the early stages of integration [32], especially in the coal sub-sector [33]. In this case, the mismatches between energy production and demand will be absorbed by the energy storage system (Fig. 1).

The transformation of these galleries into energy storage infrastructures in the form of compressed air (CAES infrastructure, iCAES) would lead to their use for storing renewable energy from excess wind and solar power.

However, the selection of the appropriate infrastructure involves a multi-criteria problem that must be supported by mathematical algorithms to evaluate and determine the most appropriate one [34]. Among all the algorithms considered from multi-criteria decision making (MCDM) methods, the Analytic Hierarchy Process (AHP) is the one proposed in this paper for its simplicity and strength in the results achieved [35,36,37] and because its use has been applied to solve similar problems [38–40] for CAES projects.

This research proposes a tool to select suitable abandoned underground mines to be used as sustainable energy storage. For this purpose, different technical, social, and economic criteria will be defined and described. Its application allows selecting the most suitable mine and reduces the risk of developing this infrastructure in this emplacement.

In this study, the application of the method is done in an absolute term and establishes a pattern to compare coal mines already abandoned in Leon region (Spain) to select the most suitable location to implement an iCAES.

2. Material and methods

2.1. Structure considered – iCAES

In general, geological structures that enable safe and stable confining are considered in the CAES technology. For example, the only two industrial references (McInthos and Huntorf) developed the "storage container" in salt domes. However, the optimal design of underground storage requires a significant investment cost for its construction and a suitable location (there are options in Spain, but their exploitation is limited by environmental legislation).

In 2018, in order to comply with the commitments resulting from the Paris Agreement, the coal mining sector has experienced a significant decline in terms of production, as a consequence of the progressive closure of thermal power plants. This situation and the

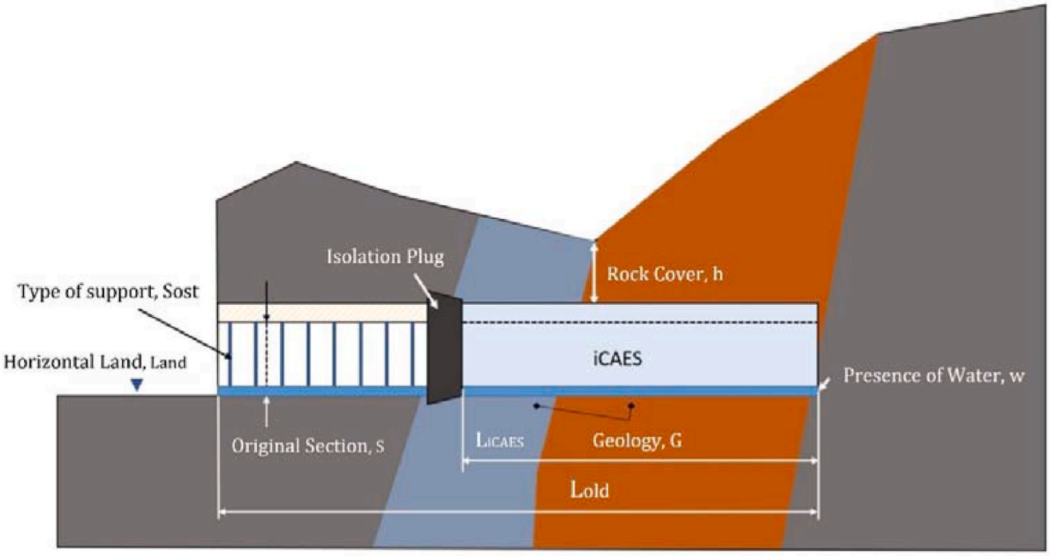

Fig. 2. Technical criteria considered in a schematic diagram.

closure of many underground coal mines in Spain with huge space and good stability have great potential to serve as compressed air storage.

Building an infrastructure (iCAES) in abandoned coal mines saves massive investments and time, so is the most cost-effective option in Spain [41]. However, it is necessary to discriminate between all options using a site selection system based on a multicriteria algorithm.

2.2. Selection criteria

One of the first consideration in designing any multicriteria algorithm is identifying the selection criteria. These criteria must be related to the initial objective: to select the most suitable abandoned coal mines as infrastructure to store compressed air (iCAES). A first breakdown of the problem needs to address both technical and socioeconomic criteria.

2.2.1 The criteria were determined utilizing literature from exploration phase in coal mines in Spain. The exploration phase is a stage prior to the exploitation of any mine. In this phase geological and geophysical studies are carried out to determine the quantity and quality of the coal present in the area. Environmental and social impact studies are also carried out to assess the possible effects of mining exploitation in the area. Also, the authors' previous experience in previous published studies has also allowed them to define the most influential for CAES technology based on literature form exploration phase in coal mines in Spain.Technical criteria.

This set of criteria considers subsoil conditions, existing infrastructure surface and engineering aspects for iCAES system (Fig. 2).

We identified three technical criteria.

(1) **Mine**. This second-level criterion refers to the site where the iCAES is to be carried out. Six thirds-level criteria are considered to stablished information about subsoil conditions, existing infrastructure, and surface.

Period of time in disuse (ta). The closure of an underground mine often does not involve maintenance of the galleries, and there may be problems of flooding or roof collapse in the main galleries that complicate the evaluation. There would also be considered issues in terms of ownership and therefore accessibility. Moreover, in some mines, dangerous atmospheres may be encountered due to the presence of methane or the absence of oxygen.

Firedamp (cg). The presence of firedamp will be a reason to dismiss the mine in order to prevent gaseous explosive atmospheres. Infrastructures in maximum safety conditions have priority.

Geology (G). The geology depends on the geographical zone however, there are two types of rocks that have an impact on the capacity to develop the energy storage infrastructure (iCAES) in technical-economic favorable conditions for this selection model: sandstones and slate (metamorphic rock, whose resistance is normally lower). This simplification allows the classification of the location with a simple collection of information from mine reports. **Gallery stability (Eg).** In this case, the criterion considers the access tortuosity, related to the number of subsidence in the gallery, either it is a complete section or not. The number of collapses also indicates the stability of the surrounding rock.

Number of bifurcations (Ps). The presence of bifurcations makes the insulation system more complex and costly: plugs pose the greatest risk of leakage.

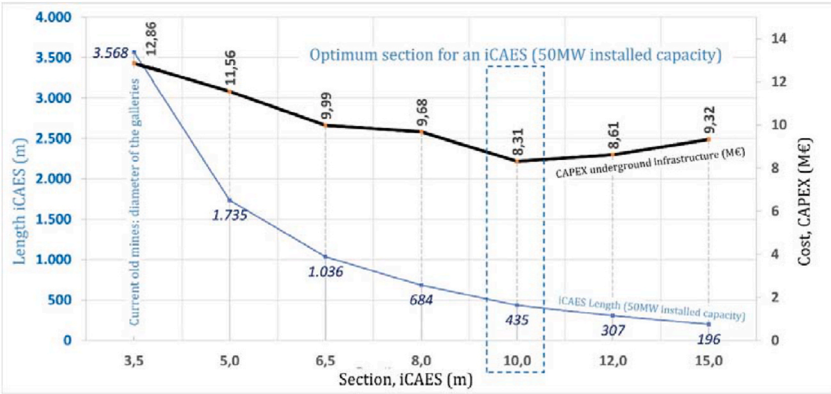

Fig. 3. Underground infrastructure CAPEX and infrastructure section and length for a 50 MW iCAES plant.

(2) **Presence of water (W).** This criterion reflects the presence of water in the gallery and studies different situations, ranging from the absence of water to the flow of a flooding.**iCAES Engineering**. This second-level criterion refers to the engineering needed to incorporate the iCAES technology in the mine. Four thirds-level criteria are considered to stablished information about engineering aspects for iCAES system.

Rock Cover (h). In order to avoid surface effects (rise in the ground, subsidence) this variable should be considered. This measurement must be made along the entire length of the iCAES under study (LiCAES, Fig. 2) to determine the favorable and unfavorable area. In addition, a larger rock cover (favorable) will result in better isolation and higher pressurization capacity with the same isolation design.

Original gallery section (S). Considering that the gallery (cylindrical structure) will have to be partially reconditioned, and that the reacconditionation and re-use of the gallery – mainly derived from civil infrastructure - in technically-economically feasible conditions assume a section of 12 m^2 (expected section), a relation between the existing and the new one can be established (Equation (1). Section assessment to achieve expected section to store energy).

$$S = \frac{Current\ section\ (m^2)}{Expected\ section\ (m^2)} \tag{1}$$

The selection of the optimum size (Expected Section) has been based on the technical economic research, comparing the cost of adequacy of an iCAES with the current section (3.5 m section diameter) versus the iCAES with a section enlargement. Fig. 3 shows graphically the suitability of the diameter (10 m and 12 m^2 of section) due to its lower cost compared to other possible sections.

This result is explained by: (a) the current size of the gallery requires demolishing all the existing support, making injections in the ground to improve its water tightness and applying a layer of new support in a very narrow space; (b) for smaller diameters (3.5 m–5 m), the execution costs are higher, since small machinery is used, with lower performance; (c) for diameters between 6 and 12 m, machinery with greater availability on the market can be used, which lowers costs; (d) for large diameters (over 12 m), it is necessary to execute the section in phases of excavation, complicating the execution and thus increasing costs (Fig. 3).

Type of support (Sost). Economic criteria will be the most important parameter when considering the cost of removing old gallery support. The proposed support for the iCAES infrastructure will be based on shotcrete, which will provide support and isolation to reduce compressed air leakage.

Available gallery length (L). In this case, this variable is based on the principle of infrastructure availability to carry out the energy storage project. For this purpose, it is necessary that the ratio between the available gallery distance (Lold) is as high as possible in relation to the length required to develop the iCAES (LiCAES). In this case, a ratio between both distances according to Equation (2) (Determination of the gallery length criterion) will be used.

$$L = \frac{L_{iCAES}}{L_{old}} \tag{2}$$

(3) Outer Surface of horizontal land (Land). This second-level criterion evaluates the capacity to carry out the outdoor engineering required for the development of the iCAES technology. A minimum value of 4 ha has been considered for the site of the compression (compression train and thermal energy storage or management), expansion (turbines) and operation, control, and maintenance buildings.

2.3. Socioeconomic criteria

These criteria respond to the social and economic determining factors to carry out the iCAES infrastructure.

Mining sector economy (in the period of operation). This criterion aims to be an indicator of social acceptance.

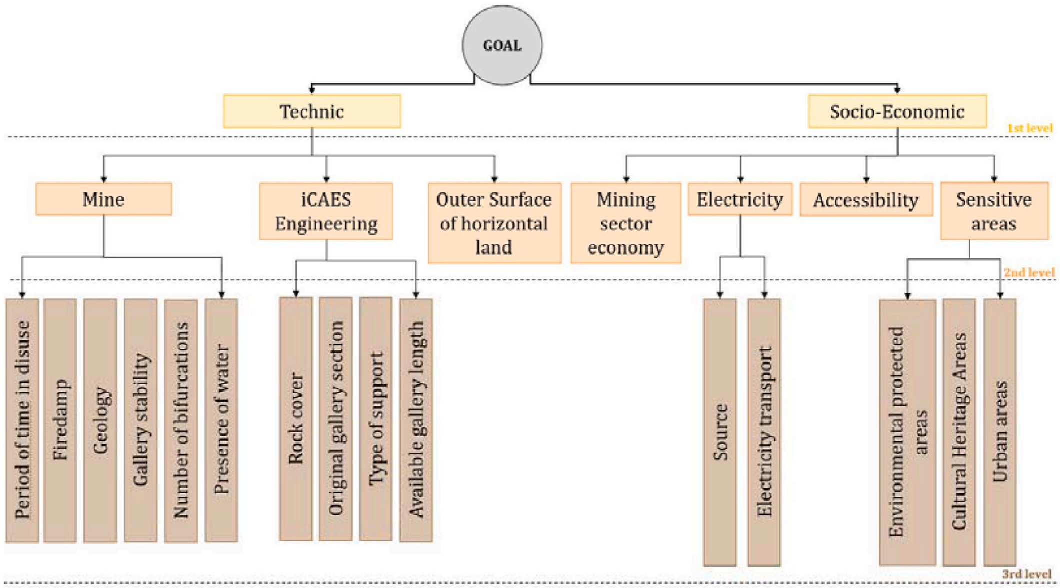

Fig. 4. Site Selection Criteria for iCAES technology.

Accessibility (A). This criterion considers aspects such as (1) climatology, which will affect the days of operation in the construction period or accessibility to mine entrance in the operation period. In a local analysis, the altitude of the mine entrance may be considered as a determining element. Also considered is the distance to major roads (2). In this point, since it will be necessary to build some facilities, such as compressors, turbines and auxiliary equipment, it is important that there are accesses that allow moving all this equipment and those necessary for the civil works to the vicinity of the mine shaft where the CAES system warehouse will be built. Therefore, another criterion to take into account is the proximity of the mine to the road.

Electricity. In this case, two third level criteria are considered: (1) Source (presence of wind farms, evaluating the power installed in the region (MW)) and (2) Electricity transport (distance to the transmission grid and access to grid nodes (km)). Both the first and the second respond to an economic evaluation: the non-availability of generation sources has an impact on the efficiency of the system by having to transport electric energy to the storage infrastructure. Similarly, the absence of evacuation networks is an obstacle to its construction. The management of licenses is another drawback. In this sense, the proximity between the abandoned mine and the thermal power plant to which it supplied primary energy is an aspect to be considered.

Sensitive areas. This criterion includes other third level criteria, which include: (1) Environmentally protected areas (NATURA 2000 NETWORK) with different levels of protection. One of the most important criteria is the environmental impact of installing a CAES system in a given location. Regardless of the environmental impact study that may have to be carried out as a requirement for its installation, within the framework of this research, the criterion for selecting possible compressed air storage facilities is that the mines selected should be far from the networks of natural parks and areas of special conservation. (2) Cultural and heritage areas. Avoid any patrimonial area in order to avoid any administrative procedures related to this type of zone. (3) Urban areas. Although the storage of compressed air for CAES technology represents a minimal risk, because the liquid is compressed and stored underground and has no deflagrating or explosive properties, a safety distance must be established.

2.4. Structure hierarchization and selection

Multiple Criteria Decision Analysis (MCDA) evaluates the alternatives of various qualitative and/or quantitative criteria and results in a solution based on priorities. The AHP (Analytic Hierarchy Process) method was introduced and defined by Thomas Saaty in 1977 as an effective tool to deal with complex decision-making and can help to set priorities (subjectively) to make the best feasible decision [42]. It owes its popularity to its simplicity and performance since it is logically compressible and could be used in different scenarios.

The AHP tool allows setting priorities to make the right decision by decomposing a complex (objective) problem into a hierarchical structure composed of several levels of abstraction (criteria and sub-criteria). For the application of the absolute AHP method, a reference pattern or model is defined, and it is compared to other alternatives. The advantage of applying the absolute method over the relative method is that the latter al-lows comparison between only seven alternatives.

In this case, we propose the decomposition of the problem into two first level criteria: technical and socio-economic. The methodology can be summarized in several steps:

- Problem structuring. Description of criteria and sub-criteria that allow carrying out a quantification.

Technical and Socioeconomic criteria (1, ..., n)		Mathematical Scale (AHP methodology)				
N level	N+1 level	1	3	5	7	9
		Equal importance		*Strong importance*		*Extreme importance*
		Scientific / technical values				

Fig. 5. Diagram and transfer between the scientific and mathematical scale. AHP, Analytic Hierarchy Process.

Table 1
Scientific values and their assignment to the mathematical scale suggested by the AHP method for Socioeconomic criteria. In the study of the case: ideal site for develop an iCAES in abandoned coal mines in Leon region (Spain).

Criteria and sub-criteria		Mathematical scale (AHP) → values		
		1	5	9
Mining	Mining sector and economy	<1% GDP	<10% GDP	>20% GDP
Accessibility	Distance to main roads (dv), km	>25	(10, 25)	<10
	Climatology/altitude mine entrance, m	>1500	(900, 1500)	<900
Electricity	Renewable generation sources, MW	<10	<50	<100
	Distance to evacuation points, km	>25	<10	0
Sensitive Areas	Urban centers, km	<20	[20,30]	≥30
	Environmental areas	Natural Park	LIC, ZEPA	None
	Cultural heritage areas	<5	5	≥10

Once the details and criteria that make up the selection problem have been studied, the problem to be solved has been structured according to Fig. 4. The criteria described in the previous section have been structured in different levels. The proposed structure responds to the division of criteria until reaching those that are quantifiable and therefore measurable. Among the technical criteria, a series of second level criteria have been defined (fixed, engineering and surface), where the first criteria have quantifiable third level criteria.

Within the technical criteria, eleven criteria were identified. The AHP method established the incompatibility of maintaining the consistency of the peer-to-peer comparison in the evaluation of more than seven elements. Therefore, a structuring has been proposed where five of the criteria can be considered fixed and the other five as engineering criteria. It will be the latter that can be modified in the re-use of the gallery for use as iCAES.

- Evaluation of each criterion (Vi) with a mathematical scale (Fig. 5).

The foundation of Dr. Saaty's process rests on the fact that it allows numerical values to be given to the judgments given by people, managing to measure how each element of the hierarchy contributes to the level immediately above it.

For these comparisons, ratio scales are used in terms of preference, importance, or probability, based on a numerical scale proposed by himself.

Saaty, which ranges from 1 to 9. Once the final result is obtained, the AHP allows the sensitivity analysis to be carried out.

- Assignment of weights to each criterion (Wi). The weight estimation will be carried out by pairwise comparison matrices, and the normalization of weights, according to the hierarchical structure built for this purpose.

Each alternative under study is evaluated, taking into account the AHP model (that we will build explicitly for the objective defined), considering the following equation, which is the AHP equation for the evaluation of the alternatives under study.

For each alternative (A1) will need a specific weight (Wi) for each criterion (in different levels) and values (Vi) (Equation (3). Evaluation of the alternatives (AHP method)).

$$A_1 = \sum_{i=1}^{n} W_i \cdot V_i \tag{3}$$

In this study, a total of ten alternatives will be evaluated as a result of the application of the proposed methodology through the AHP method. Each one of the alternatives under study will be evaluated considering the model that will be built explicitly for this objective, considering equation (3)

3. Results

In accordance with the purpose of selecting the best underground mine in León region (Spain) for an iCAES from among the alternatives considered, the calculation model (based on the AHP multi-criteria algorithm), once the decomposition structure is completed (Fig. 4), proceed to calculate each term of equation (3).

Table 2
Scientific values and their assignment to the mathematical scale suggested by the AHP method for technical criteria. In the study of the case: ideal site for develop an iCAES in abandoned coal mines in Leon region (Spain).

Criteria and sub-criteria	Mathematical scale (AHP) → values		
	1	5	9
Period of time in disuse (ta)	>20	<10	0
Firedamp (cg)	5th category	3rd category	1st category
Geology (G)	Slate (70%)	Sandstone (50%)	Sandstone
Gallery stability (eg)	>1 subsidence	>1 subsidence	Without subsidence
Rock cover (h)	<100	[200–299]	≥400
Original gallery section (S)	<0,5	0,5–0,75	≥1
Support (Sost)	Wood	Arched roof support	Shotcrete
Bifurcations per 250 m (Ps)	>4	3	1
Presence of water (W)	Water flow	Dripping/Puddle	Dryness
Available gallery length (L)	≥1	[0.75,0.51]	<0.2
Outer surface (Land)	<1Ha	2–3	>4

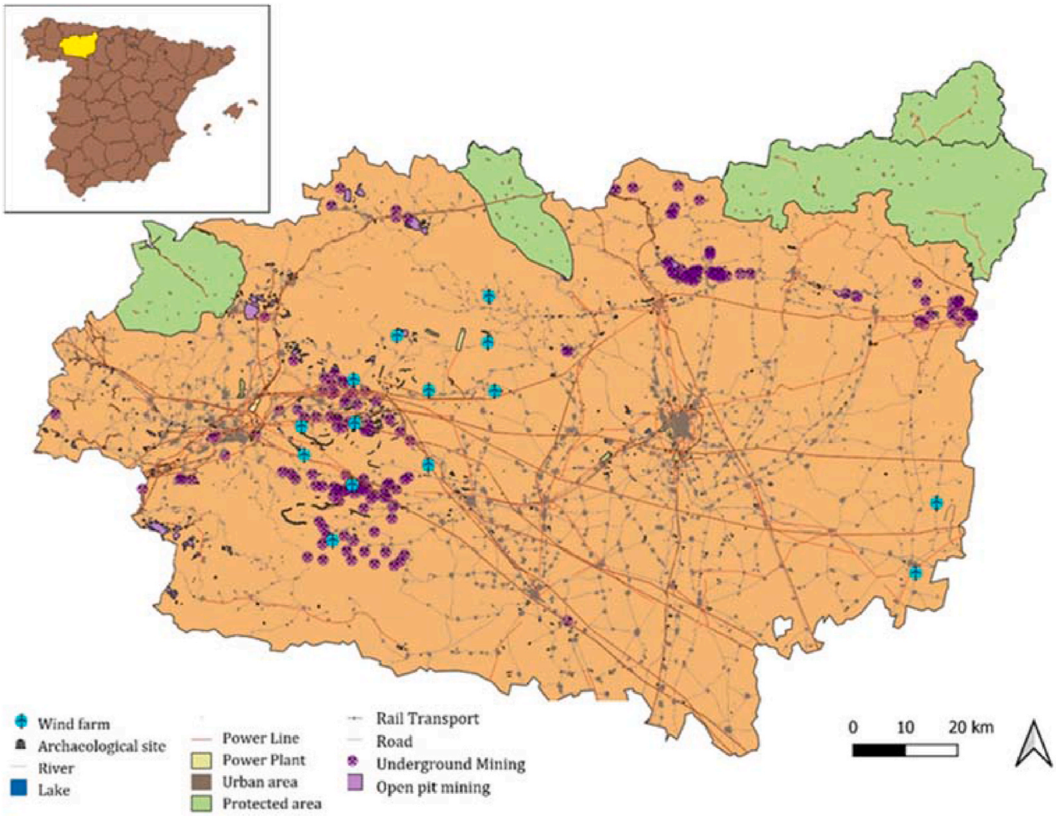

Fig. 6. Geographical Information System. Abandoned Coal Mines (León region), socioeconomic criteria.

3.1. Values (Vi)

First, assign the scientific evaluation of each quantifiable criterion, finding its translation in the mathematical scale.

According to the author's backup experience and knowledge acquired in the Smart MinEerngy Project, the scientific scale of all criteria is defined and broken into different intervals following a scientific scale defined in the AHP method. This process was defined for each valuable criterion according to the decision tree (Fig. 4). These results are shown in Table 1 and Table 2 and show the quantification work of the measurable criteria, in accordance with the scientific scale ant the assignment of values.

Table 1 corresponds to the Socio-economic criteria to carry out iCAES in a specific region in Spain (León). The researchers realized that all the scientific/technical values can be geo-referenced. To define those values a Geographic information system (GIS) was used (QGIS). The data and metadata used in the QGIS software for the construction of the SMART MinENERGY Project GIS have been downloaded from the Download Center of the National Geographic Institute and public access data provided by the Government of

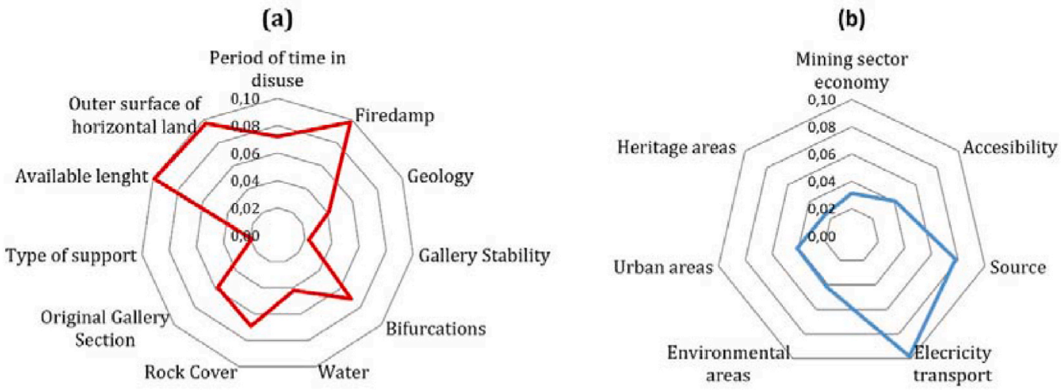

Fig. 7. Assignment of weight for each quantifiable criterion in León region (Spain). (a) Technical criteria (b) Socio-Economic criteria.

Castilla y León and EUROSTAT 2020. The result is shown in Fig. 6, included all criteria and sub-criteria corresponding to the socio-economic criteria.

3.2. Weight assessment (Wi)

After the criteria tree (Fig. 4) and values has been established, the weight can be assigned to each criterion.

The assignment begins with a pairwise comparison of the criteria and subcriteria (Equation (4). Pairwise comparison matrix, AHP method) These matrices are built sequentially, here a comparison form level to level, descending from level and relating the criteria and weights according to the relationship of nodes established in the decision tree (Fig. 4).

$$A = \begin{bmatrix} 1 & a_{12} & \dots a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots a_{2n} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & \dots 1 \end{bmatrix} \tag{4}$$

The weight is assigned to each criterion taking into account the different level criteria and will be obtained by equation (5) (Equation (5). Weight calculation, AHP method) where the judgement of value and hierarchy is assigned to the maximum eigenvalue of matrix A (Equation (4)).

$$W_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \tag{5}$$

The process of obtaining the weights (Wi) of each criterion is performed by determining the eigenvalues. In this case, the comparison between pairs of criteria has been established, and the weights obtained, as shown in Fig. 7 (Fig. 7a for technical criteria and Fig. 7b for socio-economic criteria).

The weighting of the criteria was determined by analysts of the subsidized research project (SMART MinEnergy), engineers of the Santa Barbara mine foundation, university professors of the area of knowledge (León and Madrid), specialized companies (Túneles y Geomecánica S.L.) and economic experts specialized in future energy plans.

Among the technical criteria, the available length is the first element to be considered, followed by the classification of the mine in terms of the presence of firedamp. Other criteria, such as period of time in disuse or availability of the horizontal land (suitable horizontal surface for the deployment of the surface infrastructure).

In terms of socio-economic criteria, specific accessibility to the power grid is the most important criterion, followed by the presence of sensitive areas, specifically populated or environmentally protected areas.

3.3. Alternatives (ai)

According to Equation (3), when the technical and socioeconomic criteria and their scientific mathematical scales have been determined and the normalized wights (Fig. 7), it is possible to establish a first calculation and assessment of the alternatives in the León region (Fig. 8).

AHP methodology helps decision-makers to hierarchy the alternatives under investigation and it is possible to select the most viable project, and, in addition, it is possible to identify the strengths and weaknesses of the proposal to manage the consultation and/or clarification phase in the decision-making process.

Table 3 shows the top ten suitable underground coal mines in León region (Spain) considering both socioeconomic and technical

				Weight	Alt. 1	2	3	4	5	6	7	8	9	10
WEIGHT	Wtechnical	Mine	Period of time in disuse	0,072	9	9	9	5	9	9	9	5	9	9
			Firedamp	0,098	9	9	9	9	5	9	5	5	9	9
			Geology	0,041	9	3	9	5	5	5	9	9	9	9
			Gallery Stability	0,023	9	9	9	5	5	3	5	9	5	3
			Bifurcations	0,071	9	3	9	9	9	9	3	1	5	9
			Water	0,042	9	9	9	5	5	5	9	5	1	9
		iCAES Engineering	Rock Cover	0,069	9	9	5	9	3	5	5	5	5	1
			Original Gallery Section	0,058	9	9	5	9	5	3	3	3	5	5
			Type of support	0,019	5	3	5	3	5	5	1	9	5	5
			Available lenght	0,099	9	5	9	9	3	3	3	3	9	5
		Outer surface of horizontal land		0,097	9	5	5	5	9	9	5	9	9	9
	Wsocioeconomic	Mining sector economy		0,029	9	9	9	5	5	5	3	9	3	1
		Accesibility		0,039	9	9	5	5	3	3	5	3	1	1
		Electricity	Source	0,041	9	5	5	5	3	5	9	9	5	1
			Elecricity transport	0,098	9	9	5	9	9	9	9	9	1	3
		Sensitive areas	Environmental areas	0,042	9	9	9	9	9	3	9	3	3	1
			Urban areas	0,041	9	9	5	3	9	3	5	5	3	1
			Heritage areas	0,021	5	5	5	3	5	5	5	5	1	1
				Socioeconomic	6,13	4,63	5,23	4,99	4,07	4,44	3,53	3,57	4,91	4,81
				Technical	2,72	2,55	1,84	1,99	2,12	1,70	2,22	2,07	0,70	0,51
				TOTAL	**8,84**	**7,18**	**7,07**	**6,98**	**6,19**	**6,14**	**5,75**	**5,63**	**5,60**	**5,31**

Fig. 8. Evaluation of alternatives using the AHP method.

Table 3
Second suitable Alternatives based on AHP methodology in León region (Spain).

i	ALTERNATIVES	TOTAL
1	Sarita	8.84
2	Pozo Calderón	7.18
3	Villaseca	7.07
4	Hulleras de Rioscuro o Hijos de Baldomero García (La Escondida)	6.98
5	Pozo Calderón	6.19
6	Pozo Eloy Rojo/Grupo Competidora	6.14
7	Casualidad	5.75
8	Lavadero de Viloria	5.63
9	Rolvas de la Reguera	5.60
10	Grupo Río/Cofasa	5.31

The Sarita mine, belonging to Fundación Santa Bárbara (León, Spain) has the highest valuation among the alternatives considered.

Fig. 9. Samples to be tested on Rock Mechanics Laboratory. SMART MinEnergy Project.

criteria:

Considering socioeconomic criterion Sarita and Villaseca as the most suitable mines, whereas Sarita and Pozo Calderón are the most suitable areas from technical point of view.

In this case, the mine "Sarita" is the most favorable alternative so, a campaign of extraction (carried out by The Smart MinEnergy Project) of concrete and rock cores was carried out in different areas of the mine (Fig. 9), in order to analyze and evaluate the resistance characteristics of the different materials existing in the mine to define the scientific and technical values extrapolated to the rest of the area under study (León) to re-use abandoned underground infrastructure to develop a CAES system.

Following the results obtained, it has been demonstrated that a tool is needed to prioritize alternatives to carry out the re-use of abandoned coal mines to develop an infrastructure to store air for iCAES technology to minimize risk and cost. This approach, in addition to environmental, social, and eco-nomic benefits, makes it possible to establish one of the first circular economy models.

4. Conclusions

In a context of sharp increases in the cost of energy, together with the constant increase in the concentration of CO_2 in the atmosphere and the risk of supply due to growing geopolitical tensions, Europe believes in a model based on renewable energy sources: photovoltaic and wind power.

These primary energy sources are intermittent and require backup systems or energy storage. In this research, energy storage to support grid management carried out using abandoned coal mining as an infrastructure to develop a CAES system (iCAES) in León region (Spain).

The selection of the most cost-effective abandoned coal mine has been defined as a multi-criteria problem. The use of the AHP mathematical algorithm allows structuring and breaking down the problem to compare and select all possible alternatives.

According to the results of this study, the available length is the first element to be considered, followed by the classification of the mine in terms of the presence of firedamp (technical criteria). Whereas accessibility to the power grid represent the relevant criteria from the socioeconomic point of view.

The most favorable project in León Region (Spain) according to the methodology developed in this paper is "Sarita". Thanks to this discovery, the research team has carried out the SMART MinEnergy project, where the scaling of the iCAES prototype is considered and the real operating conditions in environments with pre-industrial dimensions are evaluated.

The simplicity of the model offers a great strength in terms of the solution found the optimal underground coal mine for the location of the infrastructure for a CAES system (iCAES) so that this methodology can be extrapolated to different regions of Spain like Asturias (with presence of underground coal mines).

Author contribution statement

JUAN POUS DE LA FLOR: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

M. Cruz Castañeda: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Manuel Arlandi: Conceived and designed the experiments.

Fernando Ordás: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Juan Pous Cabello: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

CAES	Compressed Air Energy Storage
iCAES	Infrastructure Compressed Air Energy Storage
MW	Mega Watts
°C	Degrees Celsius
Ppm	parts per million
A_1	greater diameter of the cavity
W_i	Weights
V_i	Values
S	Original gallery section
m	Metre

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