Applied Energy 300 (2021) 117418

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Hubs and clusters approach to unlock the development of carbon capture and storage – Case study in Spain

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HIGHLIGHTS

- Hubs & cluster systems are recognised to greatly decrease development costs of CCS.
- Novel multi-criteria analysis is developed to identify dispersed viable CCS sites.
- Spanish case study: 15 priority clusters in 4 regions selected for CCS development.
- Up to 68.7 Mt CO_2 per year, 21% of Spanish emissions, can be decarbonised with CCS.
- CCS combined with bioenergy and blue hydrogen is key to achieve net-zero targets.

ARTICLE INFO

Keywords:
CO_2 emission hubs
Hubs and clusters
Source-to-sink
CCS site selection
Spain

ABSTRACT

Many countries have assigned an indispensable role for carbon capture and storage (CCS) in their national climate change mitigation pathways. However, CCS deployment has stalled in most countries with only limited commercial projects realised mainly in hydrocarbon-rich countries for enhanced oil recovery. If the Paris Agreement is to be met, then this progress must be replicated widely, including hydrocarbon-limited countries. In this study, we present a novel source-to-sink assessment methodology based on a hubs and clusters approach to identify favourable regions for CCS deployment and attract renewed public and political interest in viable deployment pathways. Here, we apply this methodology to Spain, where fifteen emission hubs from both the power and the hard-to-abate industrial sectors are identified as potential CO_2 sources. A priority storage structure and two reserves for each hub are selected based on screening and ranking processes using a multi-criteria decision-making method. The priority source-to-sink clusters are identified indicating four potential development regions, with the North-Western and North-Eastern Spain recognised as priority regions due to resilience provided by different types of CO_2 sources and geological structures. Up to 68.7 Mt CO_2 per year, comprising around 21% of Spanish emissions can be connected to clusters linked to feasible storage. CCS, especially in the hard-to-abate sector, and in combination with other low-carbon energies (e.g., blue hydrogen and

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https://doi.org/10.1016/j.apenergy.2021.117418
Received 5 April 2021; Received in revised form 28 June 2021; Accepted 7 July 2021

bioenergy), remains a significant and unavoidable contributor to the Paris Agreement's mid-century net-zero target. This study shows that the hubs and clusters approach can facilitate CCS deployment in Spain and other hydrocarbon-limited countries.

1. Introduction

Human activities are estimated to have caused a global temperature increase of 0.8–1.2 °C above pre-industrial levels [1]. Global warming has numerous impacts on natural and human systems, e.g., many land and ocean ecosystems and some of the services the ecosystems provide have already changed [2]. Limiting global warming to 2 °C or even 1.5 °C above pre-industrial levels will require a combination of different approaches to climate change mitigation that are compatible with sustainable development. Among the technically feasible options, CCS is widely considered an efficient and safe method for decarbonisation [3–5], and remains a core component of national and global emission reduction strategies to mitigate climate change [6,7]. For example, CCS may contribute in 14% of global CO_2 emission reduction by 2060 according to the Energy Technology Perspectives 2 °C scenario, equivalent to accumulated storage of 140 gigatons (Gt) of CO_2 [7]. In the more ambitious 1.5 °C scenario, the IPCC calculates a cumulative CCS of 550–1017 Gt by 2100 [1]. Importantly, CCS is also a key component of two technologies that could help to achieve net-zero emissions. First, CCS can be combined with hydrogen manufacture from hydrocarbons to produce "blue hydrogen", which can help to reduce emissions as a substitution of fossil fuels during the transition toward low-carbon industry [8,9]. Blue hydrogen can play an important transitional role while the entire energy system switches into full renewables [10,11]. Second, the combination of bio-energy production together with CCS (BECCS) is regarded as a core Negative Emission Technology (NET), crucial for meeting ambitious climate change mitigation scenarios [12,13]. Both technologies can help alleviate the costs related to ambitious climate targets [11,14] while promoting to the creation of a CCS industry, and thus the potential contribution of these promising technologies into decarbonisation strategies must be considered.

To date, 191 parties have submitted their "Nationally Determined Contributions" (NDC) to the Paris Agreement. Among these, more than forty countries mentioned CCS as a potential greenhouse gas (GHG) reduction method [15]. However, CCS deployment has been slow due to various barriers including: the high-cost perception of CCS development, a lack of market mechanisms and incentives, insufficient penalty mechanisms for major CO_2 emitters, an inadequate legal framework, low public acceptance, potential safety and environment issues [16,17], and uncertainty in the characterisation of storage sites [18]. According to the latest CCS database [19], there are currently 68 commercial CCS facilities and 6 CCS hubs under different development and operation status worldwide. Among these, only 28 commercial CCS facilities are in operation so far, with a maximum capacity of around 40 million tonnes of CO_2 per annum (Mtpa). A reasonable projection of the current CCS rate into the future will result in 700 Mtpa, far from the minimum 6000 Mtpa needed to achieve the 2 °C target [13]. Therefore, there is still a huge gap between the current global CCS provision and that required to meet the anticipated contribution of CCS to global and regional reduction targets. On the other hand, most commercial CCS facilities in operation are concentrated in a few hydrocarbon-rich countries with effective government support for CCS deployment, such as the USA, Canada, and Norway [19]. Most CCS projects are purposed for CO_2 enhanced oil recovery (CO_2-EOR), whereas only a few projects are for dedicated geological storage in these countries. For other countries that do not host operational commercial facilities and have to date lacked consistent government support for CCS deployment, a hubs and clusters strategy is gaining momentum and even promotes the implementation of this important technology. For example, the UK and the Netherlands are developing CCS hub projects for dedicated geological storage in the North Sea [20,21]. The hubs and clusters strategy could also be applied to other countries for dedicated geological storage, especially in hydrocarbon-limited countries.

The European Union (EU) is the third-largest greenhouse gas emitter after China and the United States, which emitted 3.89 Gt of GHG in 2018 with 3.45Gt from CO_2 emissions, accounting for around 10% of global CO_2 emissions [22]. In 2020, the EU proposed its updated GHG emission reduction target that aims to achieve a reduction of at least 55% by 2030 compared to 1990 and to achieve net-zero GHG emissions by 2050 [23]. The EU has confirmed the essential role of CCS as a technology able to significantly reduce CO_2 emissions, promoting CCS to become an integral part of the European energy policy [24], and encouraging research in it via Horizon 2020 [25] and Horizon Europe [26], the main EU Research and Innovation programmes. However, there are currently no commercial CCS facilities in operation in the EU, with only a few facilities under development in the Netherlands and Ireland [19]. There should be more scope for CCS development in the EU to achieve the ambitious net-zero target. Although the EU has sufficient storage capacity [27], the storage resource remains at a very early and immature stage with a huge gap between the requirements for a matched capacity reserve and its current inventory of large theoretical capacity resource (Fig. 1) [28]. Further assessments are needed to advance the maturity of the storage resource and thus to attract renewed interest for CCS. In addition, hydrocarbon resources are limited in many EU countries, and thus CO_2-EOR is not an option for facilitating large-scale CCS deployment.

In this study, we present a new source-to-sink assessment methodology for hydrocarbon-limited countries based on a hubs and clusters strategy and apply it in a case study in Spain. We analyse the status of Spain's CCS development, examine its potential, aim to attract renewed interest for the deployment of this important technology in Spain and show that the approach proposed in Spain can be replicated internationally. We first present the general methodology. Then, we review the current GHG emissions and the history of CCS developments in Spain to critically identify the strengths and deficiencies of CCS deployment to date. Subsequently, we carry out a detailed and systematic source-to-sink assessment. Emission hubs in different industrial sectors are identified as CO_2 sources for CCS deployment. The priority storage structure and alternative back-up structures for each emission hub are selected based on systematically screening and ranking processes using a multi-

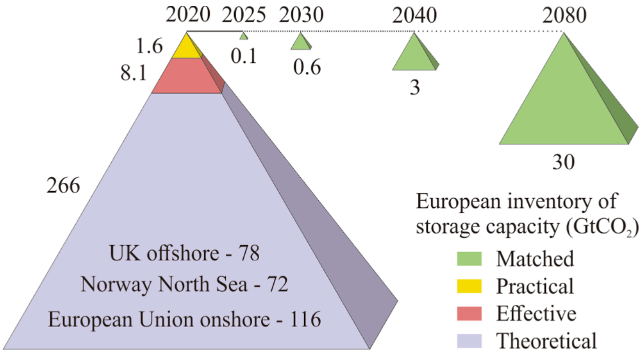

Fig. 1. Four-tier resource pyramid of European CO_2 storage capacity (in Gt) with forecasted requirements of matched capacity, framed by Carbon Sequestration Leadership Forum (CSLF) terminology: Theoretical (a regional first approximation), Effective (sum of identified prospects and exploration targets), Practical (matured prospects and candidate sites) and Matched (storage sites with bankable capacity available for injection). From Cavanagh et al. [28].

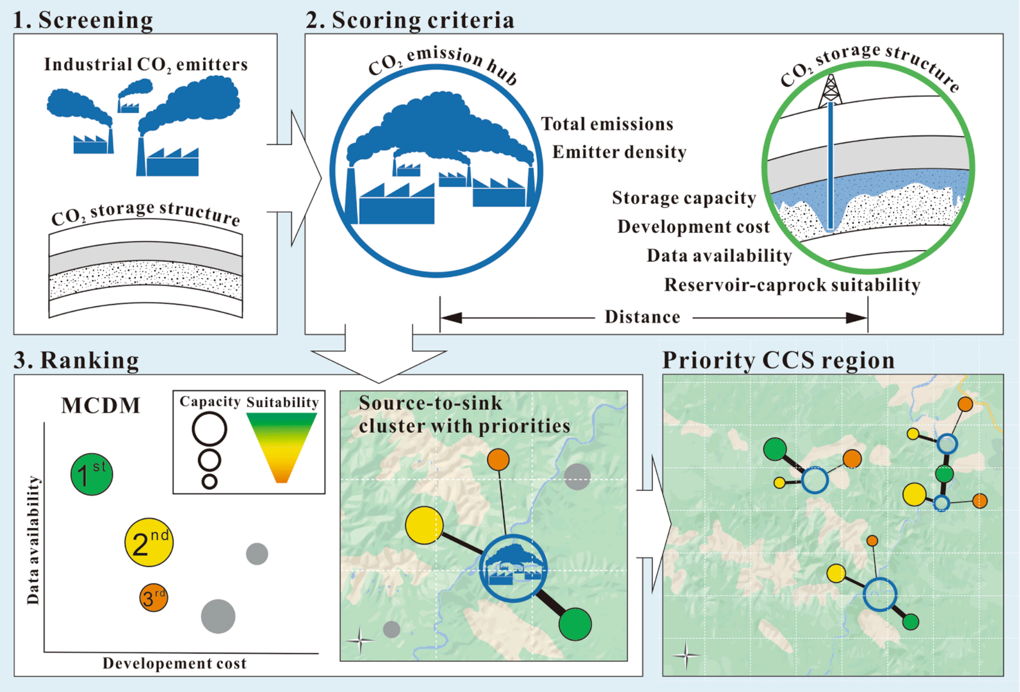

Fig. 2. Workflow of the source-to-sink assessment based on hubs and clusters strategy: Step 1, screening of the potential CO_2 sources and storage sites; Step 2, scoring criteria of potential emission hubs and storage structures; Step 3, The MCDM scheme for ranking source-to-sink cluster priorities. The ultimate goal is to identify favourable regions to deploy CCS most efficiently.

criteria decision-making (MCDM) method. Potential and priority regions are identified based on the distribution of the source-to-sink clusters. Finally, in our discussion we analyse the barriers and challenges of CCS development in Spain and explore its potential and opportunities with respect to different aspects of the CCS chain. Of particular importance is the integration of this technology with other low-carbon (e.g., blue hydrogen) or even negative emission technologies, chiefly BECCS. These technologies will likely have a key role in most countries' aims, including Spain, to meet its CO_2 reduction commitments.

2. The hubs & clusters strategy

The development of CCS has been historically closely bound to the production of oil and gas via CO_2 enhanced oil recovery (CO_2-EOR). Most of the CO_2 ever captured and injected in geological formations has been handled within the framework of CO_2-EOR projects, and the majority of the CCS projects in operation and under construction are purposed for CO_2-EOR [29]. Among the 28 commercial CCS facilities in operation, 22 facilities are for CO_2-EOR, while only a few facilities are for dedicated geological storage, located in Norway, Australia, the USA, and Canada [19]. EOR activities can provide the revenue stream that makes profitable an otherwise too expensive CCS project [30]. However, CCS can be only developed for dedicated geological storage rather than CO_2-EOR in hydrocarbon-limited countries. These countries need to devise alternative strategies if they intend to implement ambitious decarbonisation strategies via CCS development.

In hydrocarbon-limited countries, economies of scale can play a key role in reducing the costs of CCS, which in turn can incentivise investment and development in this important technology. In this sense, the implementation of CCS hubs and clusters can be an effective strategy to share the effort of developing full-chain CCS projects. CCS hubs and clusters connect multiple nearby CO_2 emitters and storage site locations to reach a critical mass for CCS development [31]. The different CCS activities such as planning, transport and storage infrastructure construction, government licensing, negotiations with property owners and so on can be shared amongst the cluster users, reducing the overall costs and risks compared with standalone projects [31]. This strategy is gaining momentum and different CCS hubs and clusters are currently being developed around the world (e.g., the Rotterdam CCUS Porthos hub in the Netherlands, the Net Zero Teeside project in the UK, or the CarbonNet project in Australia [19]). While these countries already have important hydrocarbon industries in place, we argue that this strategy can be implemented successfully in other hydrocarbon-limited countries.

In global or regional evaluations of CCS potential, multiple studies have employed source-to-sink assessments as a first-order approach, which geographically match large CO_2 emitters with basins or reservoirs, such as for global basins [32,33] or a single country [32–36]. In this study, we present a novel source-to-sink assessment methodology that not only considers the matching between CO_2 sources and storage resources but also adopts the hubs and clusters strategy. This methodology is derived and adapted from the one used for the site selection in the Acorn project of the UK North Sea [20]. The workflow created and used in this study is summarized in Fig. 2 and comprises three main steps. First, we define the potential CO_2 emission hubs as CO_2 sources for CCS development and the potential CO_2 storage sites available. Emission hubs are divided into different sectors based on the industrial types of emissions because they can play different roles in different stages of CCS development. The second step is to identify the priority source-to-sink clusters. A preliminary screening process is to select potential storage structures for each emission hub, based on basic screening criteria, such as storage capacity and distance to the emission hub. Subsequently, a scoring process is to grade the suitability of each potential storage site, involving storage capacity, reservoir-caprock suitability, development cost, data availability, etc. Finally, the scored sites are ranked and the preferred source-sink clusters are selected using a Multi-Criteria Decision Making (MCDM) process that allows selection considering multiple factors at the same time. This methodology is especially applicable for hydrocarbon-limited countries because the hubs and clusters strategy can reduce costs and hence attract interest in this decarbonisation technology. In the implementation of the methodology in different regions, specific parameters and values can be selected according to the actual conditions of evaluated objects. In the next section, we apply this methodology and present a case study of Spain, a hydrocarbon-limited country but with pressing decarbonisation needs.

3. Case study: Spain

As the fifth-largest CO_2 emitter in the EU, Spain needs to take a proactive role in meeting the EU's emission reduction target. CCS is considered a feasible option for emission reduction in Spain [37] and has been approved by the Spanish Parliament [38]. National assessments of CO_2 storage capacity and storage suitability have revealed a high potential for CCS development in Spain [39,40]. Spain had a head start on CCS in the late 2000s [41], with three pilot projects for CO_2 capture and one for CO_2 storage developed between 2006 and 2014. However, this trend was not continued. The economic crisis and uncertainty about the role of CCS in the energy transition slowed that momentum, and no commercial or demonstration projects are planned in the near future [19].

3.1. Review of CCS development in Spain

3.1.1. Deployment of capture and storage projects

Different Spanish institutions have been involved in multiple research projects related to all aspects of the CCS chain (Appendix A). Although there are currently no commercial CCS facilities active or planned, these research activities resulted in three major CCS pilot facilities developed in Spain [19].

3.1.1.1. Compostilla OXYCFB300. The Spanish Government created the CIUDEN Foundation (www.ciuden.es) in 2006, which led the public sector development of CCS in Spain. This includes the development of the Compostilla OXYCFB300 project, co-funded by the European Energy Programme for Recovery (EEPR) and the Spanish Government, and developed by a consortium of three partners: Endesa Generación, CIUDEN, and Foster Wheeler Energia Oy [42]. The Compostilla OXYCFB300 project involved the construction of a CO_2 capture and transport plant, located in the village of Cubillos del Sil (NW Spain), and a pilot project for CO_2 storage, located near the village of Hontomín (N Spain) [43]. The CIUDEN's capture technology development plant included a 20 MWth pulverised coal boiler provided with horizontal and vertical burners capable of burning from subbituminous to anthracitic type coals, and a 30 MWth circulating fluidised bed (CFB) boiler, which was the first of its kind globally for executing test runs at a large pilot scale under both air-combustion and oxy-combustion conditions [42,44]. The results of the CFB were expected to contribute to the development of the OXYCFB300 project. The storage pilot plant of Hontomín included an injection well and a monitoring well at a depth of 1.5 km, targeting CO_2 injection in a dome-shaped Jurassic carbonate formation sealed by marls [45], with an estimated capacity of 14 Mt of CO_2. The project included an ambitious site characterisation program, including the acquisition of baseline geophysical [46–50] and geochemical [51–53] datasets. CO_2 injection tests at laboratory and field scales were carried out in the fractured carbonate reservoir, one of the first in this type of reservoir, which guided the subsequent larger injection of 2300 tonnes of CO_2 [54,55]. CIUDEN also promoted a comprehensive public outreach strategy that was implemented in the Compostilla OXYCFB300 project, in parallel with the technological development activities [43]. The strategy was designed and implemented by an outreach team that concentrated on achieving interaction with the public at different levels, from local and regional to national and international. Special activities were tailored to different stakeholders, and the socioeconomic characteristics of local areas were also considered to develop an integrated communication plan. The capture project peaked in the mid-2010s and is currently in a decommissioning stage, but the storage project is still active [56].

3.1.1.2. Elcogas. The company ELCOGAS S.A. developed a pre-combustion CO_2 capture and H_2 production pilot plant with a 335 MW Integrated Gasification Combined Cycle (IGCC), in Puertollano, an old industry centre for hydrocarbon refinery and processing located in Central-SW Spain [57,58]. The ELCOGAS CO_2 capture plant was built as part of the PSE-CO_2 project in 2010 [59], the world's first pre-combustion capture pilot in a power plant [60], setting Spain at the forefront of CO_2 capture technology [41]. The 14 MW pilot plant was capable of treating up to 2% of the total syngas generated in the IGCC plant, capturing 100 tonnes of CO_2 per day with a capture efficiency>90% on average and producing 2 tonnes of H_2 per day [61]. By 2014, the plant had captured 3,500 tonnes of CO_2 [61]. However, the power plant had accumulated a large debt by 2014. A Spanish government rescue package proposed on the basis that the ELCOGAS plant was environmentally beneficial was rejected by the European Commission. The power plant was shut down together with the CO_2 capture and H_2 production plant in 2016 [60].

3.1.1.3. La Pereda. The La Pereda pilot, located in NW Spain on the site of the coal-fired La Pereda power plant, was developed by a consortium of national and international partners including Endesa Generación, Hunosa, Foster Wheeler, and CSIC (the Spanish National Research Council), commencing in 2009 [62]. This project received EU funding through three projects: CaOling (2009–2013), ReCaL (2012–2015), and CaO2 (2014–2017) [63]. La Pereda became operational in 2012, with an aim to demonstrate the viability of post-combustion capture of CO_2 using calcium looping under conditions comparable to those expected in a large-scale plant [63]. The system included two interconnected circulating fluidised bed reactors, an absorber able to treat up to 2400 kg/h and a circulating fluid bed (CFB) calciner with a firing power up to 3 MWth [62], fed by the 50 MW power plant [64]. The plant reached capture efficiencies of over 90% for CO_2 and over 95% for SO_2 [65]. The operating company, Hunosa, is currently converting the La Pereda power plant to biomass-fuelled, but there is no news about the reuse of the capture pilot facility.

A 300 kWth plant based on the same concept of carbonation/calcination was installed in La Robla, Spain [66]. The plant was connected to a 655 MWe coal power plant, property of Gas Natural Fenosa (currently Naturgy). This plant developed the "negative emissions" concept using carbonation/calcination cycles for capture of CO_2 produced from the combustion on a fluidised bed of biomass. The pilot plant of 300 kWth in the carbonator reached capture efficiency rates of over 70% and was built in the frame of the project CENIT CO_2, as part of a collaboration between Gas Natural Fenosa and CSIC.

3.1.2. Previous evaluations of CCS potential in Spain

The EU-based GeoCapacity project (2006–2009) focused on mapping large CO_2 point sources, infrastructure, and potential for geological storage in 25 European countries [27]. The main objective of this project was to compile a European capacity assessment for CO_2 storage in deep saline aquifers and hydrocarbon reservoirs. The assessment revealed a potential for CCS development in Spain, with a total storage capacity of 14 Gt, almost entirely from deep saline aquifers. Spain was ranked as the fourth largest theoretical resource in Europe after Norway, Germany, and the United Kingdom [67].

Subsequently, the Spanish Geological and Mining Survey (IGME) conducted the ALGECO2 project (2009–2010) to mature the characterisation of potential storage structures in Spain [68]. The main objectives of this project included the identification of suitable reservoir-caprock systems, the preliminary 3D characterisation of these target structures, the preliminary estimate of storage capacities, and establishing the scientific and technical criteria to rank potential structures [69]. The total storage capacity of the 103 evaluated onshore deep saline aquifers is up to 44 Gt, with 15 highly favourable and feasible structures identified by the project [39]. This database was incorporated in the

European Commission's CO2Stop database [70]. Martínez del Olmo [40] rechecked the characteristics of these favourable structures and improved the results by complementing the inventory for all of Spain with depleted hydrocarbon fields and offshore saline aquifers.

The COMET project (2010–2013) aimed to identify and assess the most cost-effective CO_2 transport and storage infrastructure able to serve the West Mediterranean area, namely Portugal, Spain and Morocco [71]. The overall strategy of COMET comprised four fundamental tasks, including the harmonized inventory of present and future CO_2 sources and sinks in the region, the least cost modelling of national and regional energy systems, the in-depth assessment of selected transport networks, and the dissemination of the information [71]. Joint large-scale transnational infrastructures were suggested and joined on to more nationwide focused alternatives to achieve better financial performance [72]. Based on the results of the COMET project, Carneiro et al. [73] conducted a cost assessment for CCS development in the West Mediterranean area, and concluded that about 11–15 clusters of 43 storage prospects defined in the study area are cost-effective, depending on the emission mitigation scenario.

3.1.3. CCS legislation in Spain

In December 2010, the Spanish Head of State signed the country's first law on Geological Storage of CO_2, the 40/2010 Law [38], a transposition of the European Directive 2009/31/CE [74]. This law was envisaged to incorporate the regulations of the European Directive into the Spanish legal system and to adapt their use to Spain's geological, industrial and energy characteristics. This law is limited to the regulation of storage activities, and not to capture and transport activities, which are regulated under other pollution and environmental laws. 18 amendments were proposed but most of them were refused mainly due to issues relating to the jurisdiction of regional governments for the implementation of this law [75]. After the law's approval, the conflict that arose from the refused amendments between three litigating regions (Aragon, Galicia, and Catalonia) and the Central State Administration [76] was concluded with the judgement of the Spanish Constitutional Court (165/2016), which ruled in favour of the central government [77]. However, the ruling itself was not free of controversy and included a strongly-argued dissenting vote in favour of the regions [78,79].

Alenza-García [75] developed a comprehensive assessment of the 40/2010 Law, finding a strong similarity with the provisions reflected in the European Directive 2009/31/CE, hence lacking original content (as in "self-developed"). This is particularly obvious in the more immature sections of the 2009/31/CE Directive, which were not developed in the transposed 40/2010 Law. The 40/2010 Law presents a limited legal framework, which refers to future regulatory developments that have not been addressed yet. A positive aspect is the substantial technical content within the articles of the law, particularly in those referring to site characterisation and the monitoring requirements of prospective storage sites. Finally, Alenza-García [75] highlighted the presence of a penalty system, including sanctions ranging from 0.2 million euros (M€) for minor infringements and up to 5 M€ for serious infringements (e.g., leakage back to the atmosphere or the ocean).

Spain has not yet developed a regulatory framework to govern the permitting process of CCS activities. However, the case of the Hontomín Technology Development Plant can be used as a reference to support the development of industrial-scale projects [80]. Firstly, the lack of a regulatory framework for CCS deployment compelled the exploration permit to be granted within the Mining Regulation. Thus, the Mining Authority considered the Hontomín geological formations as a resource of Section B "Underground Structures" (22/1973 Law). The exploration permit allowed the assessment of site feasibility for CO_2 storage. Subsequently, the storage permit requirements were established by a Task Force built by the Mining Authority, i.e., IGME and CIUDEN. The requirements established in the 40/2010 Law were used where the existing mining regulation was not sufficient. The Task Force identified the information needed to grant the Hontomín storage permit, including dynamic modelling, surveillance and monitoring, and mitigation tools, amongst others. The storage permit was finally granted in July 2018, which may serve as a good practice guideline for regulators, operators, and administrations.

3.1.4. Cost assessments

Multiple studies identify cost as the principal barrier for the development of CCS [17,81]. Based on the analysis of Gouveia et al. [82], the adoption of CCS in the Iberian Peninsula greatly depends on the cost evolution of both renewable resources and CCS: CCS becomes cost-effective after mature renewables, namely onshore wind and hydropower, are fully exploited up to their technical–economic potential. According to the Global CCS Institute, the cost of CO_2 capture is falling because of various reasons, including improvements in solvents, newer non-solvent based capture technologies, improved CO_2 compression strategies, economies of scale, and modularisation [83]. However, the high cost of CO_2 capture is still one of the major barriers to CCS development. In the power sector, the pathway to lower costs involves a combination of advances in power generation technology and advances in CO_2 capture technologies [84]. In the remaining industrial sectors, a severe cut in CO_2 emissions within reasonable cost does not seem possible without CCS deployment, since a significant share of the emissions is process-embedded and cannot be avoided by applying measures such as a transition from fossil fuel to renewable resources [85]. In countries like Spain that have a framework of emission reduction favourable to renewables resources and energy efficiency, CCS in sectors hard to be abated via renewables (e.g., cement or steel factories) may play an important role to achieve a long-term and ambitious emission reduction target [86]. Based on a techno-economic analysis and systematic review of CCS in some industries [87], the cost per tonne of CO_2 avoided varies significantly in different industries. Spain's large CO_2 emitters ($\geq$1 Mtpa) in the hard-to-abate sector are from cement, iron and steel, and pulp and paper industries. Among these, CCS in the cement industry using calcium looping technology presents a much lower overall cost than that in the other two industries [87], and could therefore become priority sources for CCS development in Spain.

Achieving significant cost reductions of CCS deployment will require not only a vigorous and sustained level of technical research and CCS development, but also a substantial level of commercial deployment [88], which in turn will require a significant market for CO_2 capture technologies that can only be established by government actions. In Spain, a new law on "Asignación de Derechos de Emisiones Gratuitos" (i.e., Free Emission Trading), transposed from the EU's Directive 2003/87/CE [89], plans to progressively reduce the free emission rights [90]. This could lead to an increasing cost of emitting CO_2, which may promote the CO_2 capture market and make CCS economically more feasible [91]. Furthermore, the combination of CCS with other low-carbon technologies, such as bioenergy and blue hydrogen generation could help reducing the upfront costs related to CCS, via clustering and infrastructure sharing [11,13,14]. This could create an incentive to develop these technologies synergically. Developing the clean hydrogen infrastructure at the scale demanded in the clean energy strategies is unlikely to happen without blue hydrogen [92], and this is aligned with the mature renewable scenario where CCS can become cost-effective [82]. The CCS portion of BECCS strongly influences the cost of the operations [93], and therefore it is important to identify priority CCS areas for early development.

3.2. GHG emissions and reduction target in Spain

The national GHG emissions for Spain in 2018 were estimated to be 334.3 million tonnes of CO_2 equivalents ($MtCO_2eq$) [94], the fifth largest emitter in the EU after Germany, France, Italy and Poland. These emissions represent an increase of 15.5% with respect to the emissions in 1990 (289.4 $MtCO_2eq$) and a reduction of 24.7% of the emissions with respect to 2005 (428.9 $MtCO_2eq$). The GHG emissions derived from the four sectors (as defined by the Intergovernmental Panel on Climate

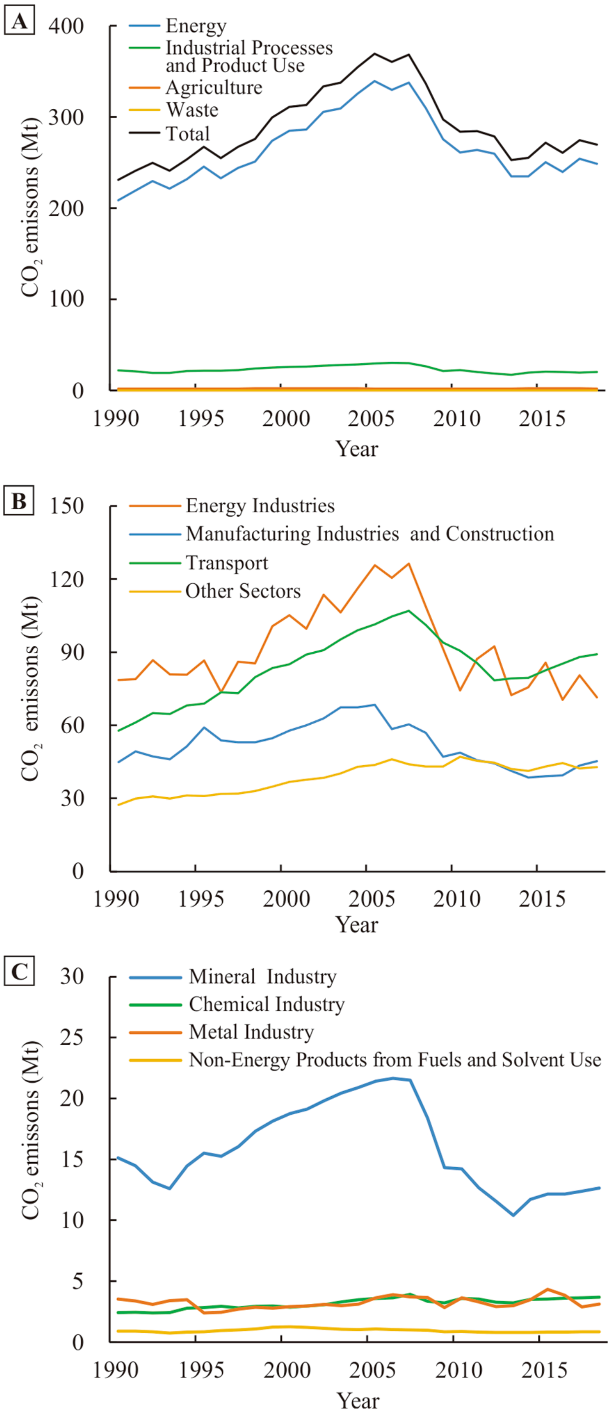

Fig. 3. National inventory of annual CO_2 emissions in Spain from 1990 to 2018: (A) CO_2 sources by sectors (as defined by the IPCC); (B) energy-related activities; (C) the industrial processes and product use sector. Data source: MITECO [94].

Change - IPCC) are: energy industries (75.8%), industrial processes and product use (8.3%), agriculture (11.9%) and waste (4.0%). The CO_2 reduction achieved in 2018 due to land use, land-use change and forestry (LULUCF) activities was 38.5 $MtCO_2eq$. Detailed discussions of GHG emission trends in Spain are discussed elsewhere [94–96].

CO_2 emissions are the main GHG source in Spain, accounting for 269.7 Mt in 2018 (80.7% of the total GHG emissions). The energy industries (including fuel combustion activities, such as electricity generation, heating and transport) with 245 Mt and the industrial processes and product use sector with 20 Mt are the most intense CO_2 emitters, representing 92.3% and 7.5% of the CO_2 emissions, respectively, while the waste and agriculture sectors mainly emit non-CO_2 GHGs (Fig. 3A). Spain has traditionally been a fossil fuel importing country, which currently accounts for 75% of its energy production: coal (10%), natural gas (21%), and fuel–oil (44%) [97]. In the energy sector, CO_2 emissions mainly come from fuel combustion activities, including transport (89.2 Mt), power generation (71.5 Mt), manufacturing industries and construction (45.3 Mt), and others (42.9 Mt) (Fig. 3B). In the industrial processes and product use sector, CO_2 emissions are mainly derived from mineral (12.7 Mt), chemical (3.7 Mt) and metal (3.1 Mt) industries (Fig. 3C).

The Spanish Government has approved the National Long-Term Decarbonisation Strategy in response to the EU's target [86]. Spain aims to achieve a GHG emission reduction of 90% by 2050 compared to 1990, equivalent to a reduction from 334.3 $MtCO_2eq$ in 2018 to 28.9 $MtCO_2eq$ in 2050. The remaining 10% of emissions will be solved by nature-based carbon sinks, e.g., LULUCF. This long-term decarbonisation strategy also aims for 100% renewable electricity generation by 2050 [39]. Spain's decarbonisation target is technologically neutral, i.e., all decarbonisation technologies should have equal opportunities to develop cost-efficient solutions in different economic sectors. This strategy is consistent with the Spanish Integrated National Energy and Climate Plan 2021–2030, published in January 2020 [98].

Both these two major decarbonisation plans released by the government highlight the importance of CCS, but are not explicit about the mechanisms, costs, benefits or dates of its implementation. Although CCS has been considered a feasible option for emission reduction in Spain [37] and approved by the Spanish Parliament [38], the explicit support to CCS development given by the Spanish government has been limited to the creation of the CIUDEN Foundation, a public sector CCS delivery (see Section 3.1 for the specific actions taken by the foundation). Given the large tonnage scale and geographic focus as point sources, CCS could be an effective tool to decarbonise the power and industry sectors.

3.3. Priority CCS region selection methodology

To identify and characterise the priority CCS development regions in Spain (i.e., target CO_2 emission hubs and their most suitable storage sites), we carry out a detailed and systematic source-to-sink assessment using the methodology presented in Section 2 and Fig. 2. The methodology is suited to the decarbonisation needs and storage opportunities of Spain, but the values chosen for the different evaluation parameters can be adapted to different emission and storage scenarios, so it can be easily adapted to other countries and contexts.

3.3.1. Screening of emission sources and storage sites

Industrial facilities with large CO_2 emissions are seen as primary sources to implement CO_2 capture in their industrial processes [99], because it is more efficient to address their emissions than from small and dispersed CO_2 emissions. In 2018, there were 183 industrial facilities with CO_2 emissions large than 0.1 Mtpa in Spain, which are classified by industrial sectors in Fig. 4A [100,101]. These large CO_2 emitters have total emissions of 110.5 Mtpa (41% of Spain's total emissions), with 83 CO_2 emitters in the power industry accounting for 71.3 Mtpa, while 100 CO_2 emitters in other industries accounting for 39.2 Mtpa. In the power industry, CCS is not the only option for decarbonisation. Indeed, emissions can be mitigated by other methods in the future, e.g., switching to renewable resources and improving energy efficiency. Coal-fired power plants are some of the largest single CO_2 emitters in Spain, and the government has established a plan for the closure of these plants [102,103]. However, an early penetration of CCS in the power sector is needed to achieve ambitious mitigation targets in Spain [82].

On the other hand, emissions from other industries, including metal,

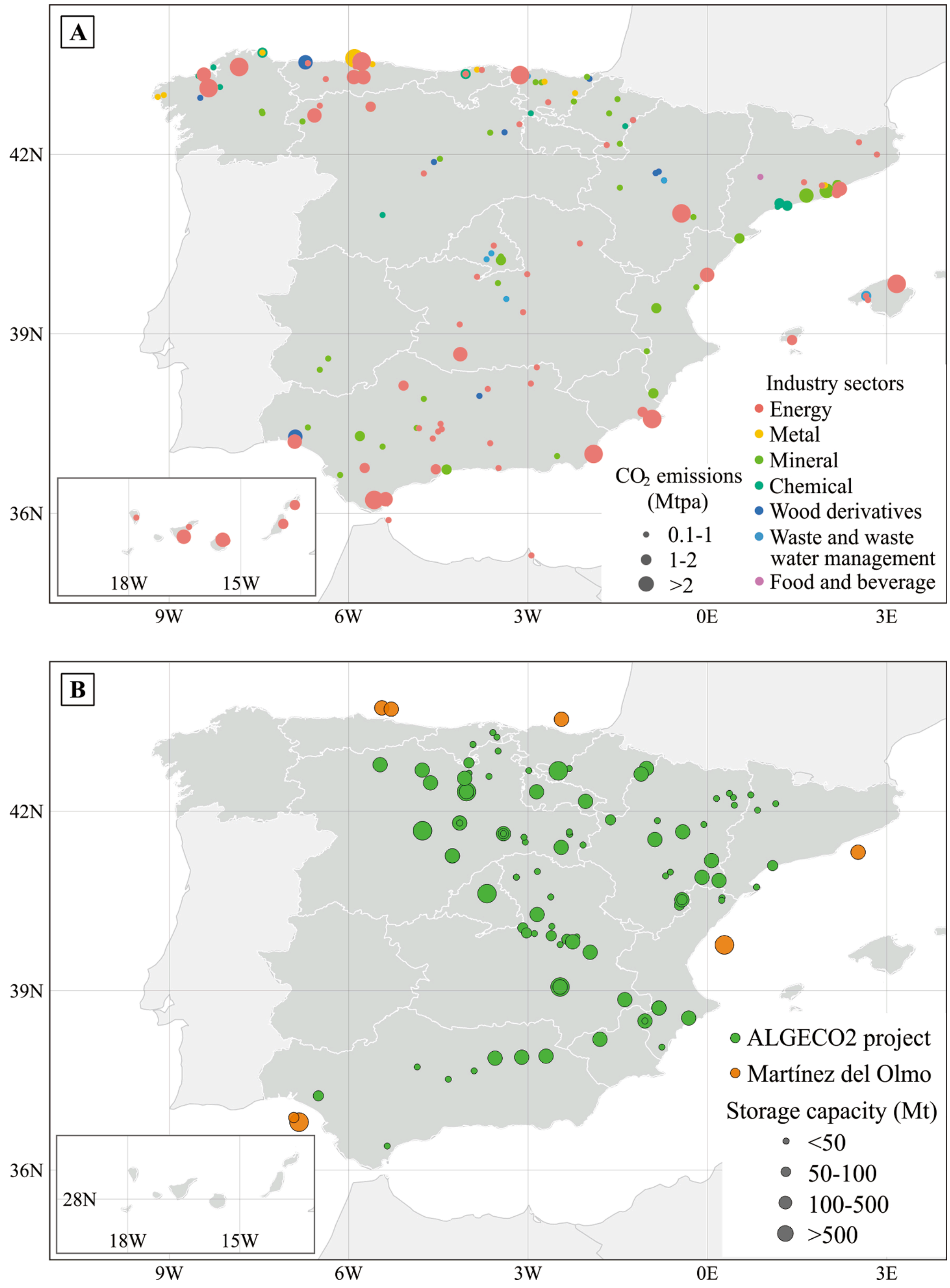

Fig. 4. (A) Large industrial sources of CO_2 emissions ($\geq$0.1 Mtpa) by industrial sectors in Spain in 2018. Data source: [100,101]. (B) CO_2 storage structures in Spain from the ALGECO2 project [68] and Martínez del Olmo [40].

mineral, chemical, wood derivatives, waste and waste-water management, and food and beverage industries (hereby called "hard-to-abate sector") cannot be mitigated by using renewable energy or by improving energy efficiency due to the existence of process-related emissions. Thus, we separate these two sectors to allow the exploration of CCS deployment at two development stages, one more immediate (to decarbonise the power system) and one more sustained (to decarbonise other industrial systems).

For economies of scale, transport networks would need to serve multiple facilities and/or storage sites [4,104–105]. In this study, CO_2 emission hubs include potential CO_2 sources for CCS development within a circular area with a diameter smaller than 60 km and annual CO_2 emissions higher than 2 Mtpa. The values of 60 km and 2 Mtpa were chosen based on the distribution of these large CO_2 emitters, trying to minimise the number of clusters and maximise the CO_2 emissions per cluster without making clusters too large.

Finally, the CO_2 emissions in the Canary Islands present relatively high emissions derived from their heavy dependence on external energy sources, chiefly oil [106–107]. However, none of the storage portfolios have identified any suitable geological structures onshore of any the islands. Due to its distinct geographical location and remoteness from mainland Spain, the implementation of CCS in the Canary Islands was not included in this work. A specific study addressing the specificities of this archipelago is nevertheless strongly advised.

For the screening of the storage structures, geological data from 110 storage sites were extracted from previous studies, including 103 onshore saline aquifers from the ALGECO2 project [68] and 7 offshore saline aquifers [40] (Fig. 4B). For each emission hub identified in the

Table 1
Criteria to evaluate the availability of seismic and well data (0 for low availability, to 3 for high availability).

Data availability	Seismic density	Well number
3	High (3D)	≥5
2	High (2D)	3–4
1	Low (2D)	1–2
0	None	None

previous step, a preliminary screening process is applied to all storage sites to determine whether they are taken forward or disqualified. This preliminary screening is based on two basic criteria: theoretical storage capacity and source-to-sink distance. This screening process reduces the input structures to a more manageable number and allows the selection of potential structures for each emission hub for the following ranking process. We assume that potential storage structures must have a capacity large enough so that they can store 90% of the thirty-year CO_2 emissions of the respective emission hub based on the capture efficiency, generally assumed as 90% [108]. The maximum source-to-sink distance has been set to 200 km to limit transport and monitoring costs. The distance limitation is extended to 300 km if fewer than five structures pass the screening process for an emission hub.

3.3.2. *Scoring*

For each emission hub, the filtered potential structures are scored based on four criteria including theoretical storage capacity, the suitability of reservoir-caprock systems, development cost, and the availability of seismic and well data for their assessment.

3.3.2.1. Storage capacity. Storage capacity is positively correlated with the ranking of the storage structures. High storage capacity is required to guarantee the selected storage structures are economically suitable and capable of storing all CO_2 from the emission hub. Storage capacity, even in the form of static volume, can also have an influence on the unit cost of CO_2 stored: assuming a similar capital expenditure of prospective CCS projects, the larger the storage capacity, the lower the unit cost of CO_2 stored because of the economy of scale [20].

3.3.2.2. Reservoir-caprock suitability. To evaluate the suitability of reservoir-caprock systems, five parameters are adopted from the ALGECO2 database and Martínez del Olmo [40]: the effective thickness, porosity and permeability of reservoirs, and the effective thickness of caprocks and the presence of fractures within caprocks. For reservoirs, porosity is here used as a proxy for effective capacity, and effective thickness and permeability are used as proxies for injectivity. Due to the lack of permeability data in the offshore storage structures from Martínez del Olmo [40], an indirect permeability value was inferred from porosity based on the correlation (trend line) between permeability and porosity of onshore storage structures. Whilst not a perfect predictor, porosity and permeability are correlated and so permeability is estimated from known porosity. For caprocks, high effective thickness and low presence of fractures are used as a proxy for high-sealing capacity [109]. The presence of fractures in caprocks was estimated in an expert elicitation carried out in the framework of the ALGECO2 project [68]. To quantitatively evaluate the suitability of reservoir-caprock systems, the presence of fractures in caprocks is assigned a value: 1 for high, 2 for medium and 3 for low presence level of fractures. Then, we applied a data normalisation to all five parameters based on a function of their minimum and maximum values to achieve non-dimensionalisation of these parameters:

$$V_n = \frac{V - V_{min}}{V_{max} - V_{min}} \tag{1}$$

where V_n, V, V_{min} and V_{max} are the normalised, actual, minimum and maximum values, respectively. The five normalised parameters add up to the total suitability score of each storage structure.

3.3.2.3. Development cost. To provide a proxy for the development cost, we consider both the pipeline construction for CO_2 transportation and well drilling for CO_2 injection. The development cost of onshore and offshore structures is calculated based on a 5-well storage system [20]:

$$Cost_{onshore} = l\hat{A}\cdot P_{onshore} + 5\hat{A}\cdot d\hat{A}\cdot D_{onshore} \tag{2}$$

$$Cost_{offshore} = l_{onshore}\hat{A}\cdot P_{onshore} + l_{offshore}\hat{A}\cdot P_{offshore} + 5\hat{A}\cdot d\hat{A}\cdot D_{offshore} \tag{3}$$

where l is the distance from onshore structures to the emission hubs, $l_{onshore}$ and $l_{offshore}$ are the onshore and offshore distances from offshore structures to the emission hubs, d is the middle depth of the storage reservoir, $P_{onshore}$ and $P_{offshore}$ are the cost of onshore and offshore pipeline construction per kilometre, and $D_{onshore}$ and $D_{offshore}$ are the cost of onshore and offshore borehole drilling per kilometre. All costs in this section are in 2020€. $P_{onshore}$ is assigned a value of 0.88 M€ per kilometre based on the onshore pipeline capital cost in a scenario with a pipeline diameter of 24 in. [110]. $D_{onshore}$ is assigned 1.56 M€ per kilometre based on data collected from the report of oil and gas upstream costs in the U.S. [111]. $P_{offshore}$ is assigned 1.47 M€ per kilometre based on the offshore pipeline costs in the Gulf of Mexico in a scenario with a pipeline diameter of 14 to 24 in. [112]. $D_{offshore}$ is assigned 7.78 M€ per kilometre based on the offshore well drilling cost per kilometre reported by Hinton [113] and the average well cost breakout reported by the U.S. Energy Information Administration [111].

3.3.2.4. Data availability. The availability of seismic and well data is crucial to guarantee the certainty of storage capacity and the suitability of reservoir-caprock systems. Existing data can also be used in CCS deployment and thus reduce the development cost. To determine the data availability factors, we only considered datasets included in the Spanish Geological Survey's repositories, in both ALGECO2 [68] and the Spanish Geophysical Information System [114]. The availability of seismic data is graded into four levels (Table 1). 3D seismic data is assigned a value of 3 representing the highest data availability, which only covers a few of the offshore structures. 2D seismic data is subdivided into "high 2D" and "low 2D" and assigned values of 2 and 1, respectively, based on the density of survey lines. A value of 0 is assigned to structures that are not crossed by any seismic line. Similarly, the availability of well data is also divided into four levels based on the number of wells (Table 1). The final data availability value is the sum of the availability of seismic data and well data.

3.3.3. *Ranking*

After defining and quantifying the four ranking criteria, the MCDM method is used to rank potential storage structures for each emission hub. MCDM is a branch of operational research dealing with finding optimal results in complex scenarios including various indicators, conflicting objectives and criteria [115]. MCDM methods have been applied in many aspects of the CCS chain, e.g., barrier analysis [81] and the selection of storage sites [116]. It has been proven as an effective method in the assessment of CCS in Spain [117–119]. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method [120] is adopted in this study. This method is a compensatory process, i.e., a poor result in one criterion can be negated by a good result in another criterion, thus no alternatives are excluded due to a single poor result in one criterion. TOPSIS is very suitable to explicitly evaluate multiple conflicting criteria in decision-making. For one emission hub, the values of each criterion for all potential structures are normalised and weighted based on the following method:

$$Y_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^{2}}}\hat{A}\cdot W_i \tag{4}$$

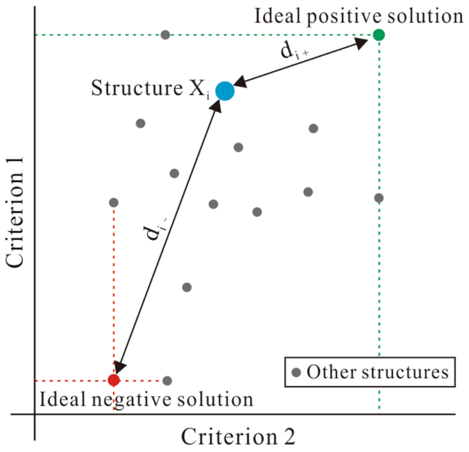

Fig. 5. Scheme of the ranking methodology adapted from the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [120]. The structures are defined in a multidimensional space determined by their values in each of the four ranking criteria. The best and worst values of the structures in each criterion determine the ideal positive and negative solutions, respectively. The distances to these ideal positive (d_{j+}) and negative (d_{j-}) solutions are combined into a TOPSIS score (Ts), which is therefore dependent on all criteria at the same time.

where Y is the normalised and weighted value, X is the actual value, W is the weighting of the criterion, i is the number of potential structures for the emission hub and j is the number of the criteria (four criteria in this study). Once the values of all criteria for all potential structures are normalised and weighted, a pair of positive and negative ideal solutions are hypothesised based on the best and worst values for each criterion; i.e., the positive ideal solution is the one that maximises the positive criteria and minimises the negative criteria, and vice versa (Fig. 5). The distance (i.e., differences) between each structure to the positive and negative ideal solutions are calculated. Finally, the TOPSIS score (T_s) of each structure is calculated as:

$$T_s = \frac{d_+}{d_+ + d_-} \tag{5}$$

where d_+ and d_- are the separation from the ideal positive and negative solutions, respectively.

The criteria are not equally considered when assessing the suitability of a storage site. Hence, a relative weighting is applied to the different criteria values to reflect this variability. The weighting of each criterion has been chosen subjectively, based on the authors' best knowledge and is listed as a percentage in Table 2. Three weighting scenarios are applied: geological, economic and a combined scenario. The geological scenario assigns higher weightings to storage capacity and the suitability of reservoir-caprock systems and lower weightings to development cost and the availability of seismic and well data compared to the economic scenario. When the two scenarios result in different priority structures for one emission hub, the final result is determined by the third scenario which uses averages of the two scenarios weightings, here defined as "comprehensive scenario".

The MCDM method has been implemented using Microsoft Excel. The specific assessment process and result for each emission hub can be found in the Supplement (Appendix B). After the ranking of potential storage structures for each emission hub, the priority structure is identified, and the second- and third-best structures are listed as alternatives.

4. Results

4.1. CO_2 emission hubs and priority source-to-sink clusters

The application of the methodology presented to the Spain case resulted in the selection of 15 CO_2 emission hubs as potential CO_2 sources for CCS development. These emission hubs emit 68.7 Mtpa of CO_2, representing 20.6% of Spain's GHG emissions in 2018, so the contribution of CCS in decarbonizing Spain could be significant. Among these, 11 emission hubs are in the power sector and have total CO_2 emissions of 52.8 Mtpa (Fig. 6A, Table 3), which mainly come from thermal power plants and oil refineries. The remaining four emission hubs belong to the hard-to-abate sector and have total CO_2 emissions of 15.9 Mtpa (4.8% of Spain's GHG emissions in 2018) (Fig. 6B, Table 3), which are mainly derived from iron and steel production, cement production and pulp production. The emission hubs are mainly distributed in coastal areas, e.g., Galicia, Asturias, the Basque Country, and Catalonia in northern Spain, and Murcia and Andalusia in southern Spain (Fig. 6).

The priority and alternative storage structures most suitable to the 15 emission hubs were identified after the screening and ranking stages, leading to 15 priority source-to-sink clusters and their alternative structures, whose detailed features are listed in Table 4. Of these, 9 priority structures rather than 15 were selected because some adjacent emission hubs share the same potential storage locations. These priority and alternative structures are mainly distributed in Castilla and Leon, Asturias, and Aragon in northern Spain, and Murcia and Andalusia in southern Spain, with a few offshore storage structures (Fig. 7).

4.2. Potential development regions outline

Four potential CCS development regions in Spain are identified based on the distribution of priority source-to-sink clusters and their alternative storage structures (Fig. 7). The development regions need to meet two requirements:

- They should contain multiple emission hubs. Three of the four identified regions have emission hubs from both the power sector and the hard-to-abate sector, and one region only contains power emission hubs. The emission hubs from different sectors are necessary to ensure that the identified regions can play potential roles in different development stages of emissions reduction, as explained in Section 3.1.1.
- They should also contain multiple potential storage structures, especially the structures shared by multiple emission hubs, which are beneficial to the development of large CCS regions in the future.

4.2.1. North-Western Spain region

North-Western Spain region has five emission hubs with total CO_2 emissions of 33.4 Mtpa, accounting for almost half of the emissions of all emission hubs. E1, E2 and H1 are the three largest emission hubs in Spain, with CO_2 emissions of 11.6, 10.3 and 7.1 Mtpa, respectively. The E1 and E2 hubs include the two largest emitters in the power sector in

Table 2
Weighting scenarios of four ranking criteria in the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method.

Criteria Scenarios	Storage capacity	Suitability of reservoir-caprock systems	Development cost	Data availability
Geological scenario	25%	40%	25%	10%
Economic scenario	15%	30%	35%	20%
Comprehensive scenario	20%	35%	30%	15%

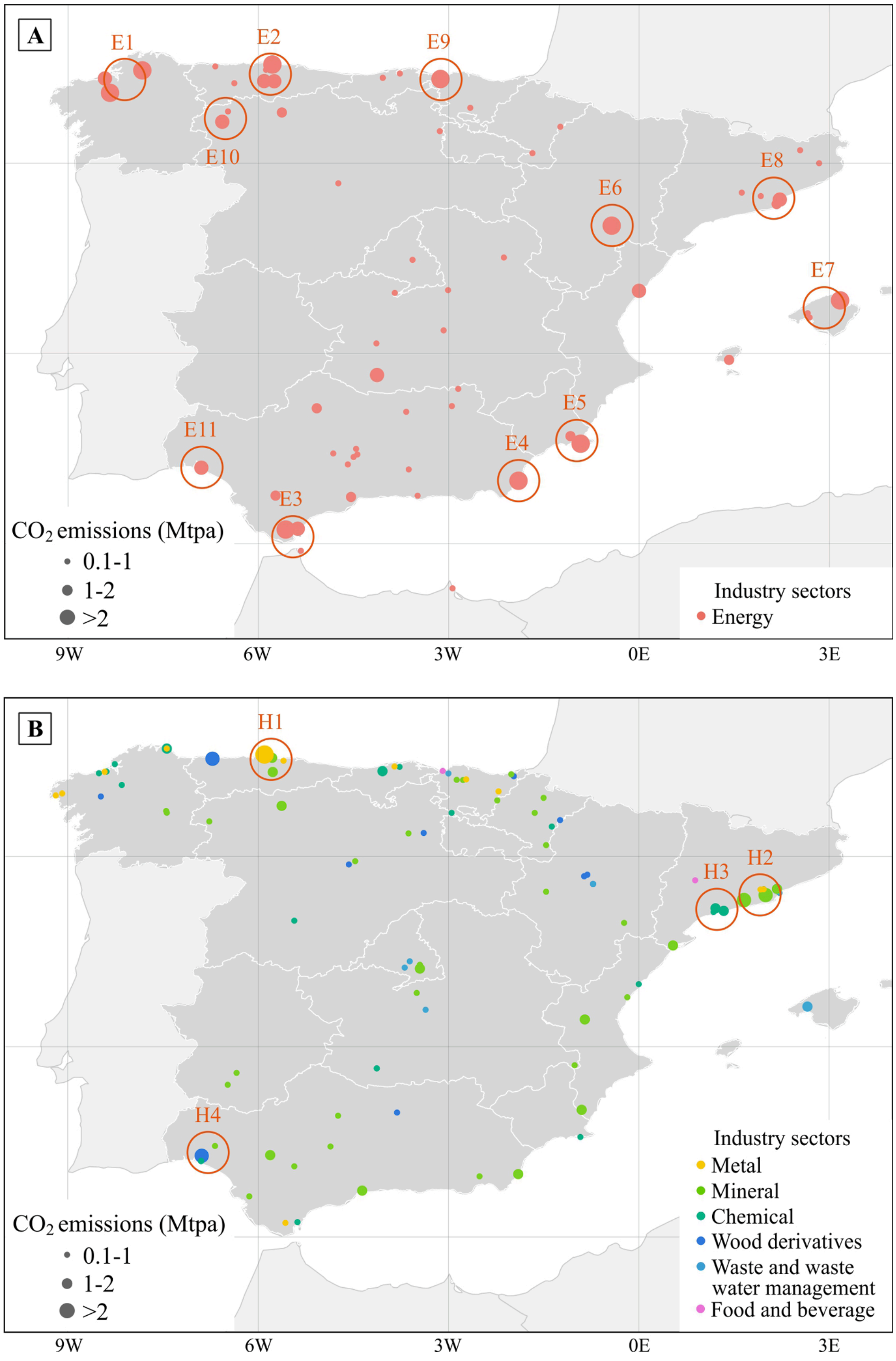

Fig. 6. Distribution of identified CO_2 emission hubs: (A) 11 emission hubs in the power sector; (B) four emission hubs in the hard-to-abate sector.

2018, Unidad de Producción Térmica As Pontes (closed in 2020) and Central Térmica de Aboño, which are two thermal power plants emitting 7.9 and 7.1 Mtpa, respectively. The H1 hub has the largest emitter in the hard-to-abate sector, ArcelorMittal Asturias, an iron and steel enterprise with emissions of 5.7 Mtpa. The E1 hub is located in the north-western corner and far from potential structures. Although the source-to-sink distance was extended to 300 km, the priority structures of other emission hubs were not placed within this radius. Its priority structure is an offshore structure, Mar Cantábrico J-1 S. The E2 and H1 hubs share the same priority and alternative structures due to their proximity. The priority structure, Iglesias (Utrillas), has a high capacity, a good reservoir-seal system and reliable seismic and well data. The priority structure of the E9 hub, Rioja Norte (pre and *syn*-orogenic Tertiary), has a very large storage capacity (>500 Mt). However, it is located in pre-orogenic sediments and at depths>3,500 m (reaching up to 5,000 m depth), which is far from the optimal storage depth [121] and could significantly increase the drilling cost. Thus, Iglesias (Utrillas) could be regarded as a good alternative structure for the E9 hub. The priority structure of the E10 hub, Duero Centro-Meridional (Upper Cretaceous), has also suitable features for CO_2 storage but lacks sufficient seismic data, resulting in high uncertainty.

Table 3
Annual CO_2 emissions for identified emission hubs, divided into the power sector and the hard-to-abate sector, and location of the hub centroid in latitude and longitude (WGS84).

Power sector					Hard-to-abate sector				
Hubs	No. Sites	Emission (Mtpa)	Latitude	Longitude	Hubs	No. Sites	Emission (Mtpa)	Latitude	Longitude
E1	4	11.6	43.34	−8.12	H1	5	7.1	43.51	−5.8
E2	6	10.3	43.4	−5.84	H2	9	4.2	41.43	1.91
E3	9	6.3	36.19	−5.39	H3	4	2.3	41.16	1.24
E4	1	6.3	36.99	−1.9	H4	5	2.3	37.26	−6.85
E5	3	3.2	37.62	−0.98					
E6	1	3.1	41.01	−0.43					
E7	3	2.8	39.68	2.84					
E8	5	2.8	41.44	2.03					
E9	1	2.3	43.32	−3.11					
E10	2	2.1	42.73	−6.53					
E11	3	2	37.2	−6.9					
Total	38	52.8			Total	23	15.9		

4.2.2. *North-Eastern Spain region*

Five emission hubs are located in North-Eastern Spain region: E6, E7, E8, H2 and H3, with CO_2 emissions between 2.3 and 4.2 Mtpa, which together account for 22% of the emissions of all hubs. The main emitters include two thermal power plants, Central Térmica de Andorra (closed in June 2020) with emissions of 3.1 Mtpa and Central Térmica de Cicle Combinat with 1.4 Mtpa, as well as two cement enterprises with emissions of around 1 Mtpa (Cementos Molins and Cementos Portland Valderrivas). The E6, H2 and H3 hubs share the same priority structure, the Área de La Zona de Enlace (Buntsandstein), which has very good reservoir quality, but a relatively high uncertainty in the effective thickness of caprock due to the lack of seismic data coverage. Thus, other structures, e.g., Barcelona-A, Reus and Caspe-Mayals, can be seen as good alternative structures for these emission hubs. The priority structure of the E8 hub is Barcelona-A due to their proximity. The E7 hub is located in the Balearic Islands, which is relatively far from potential structures (only a few onshore and offshore structures are located within a distance of 300 km). Its priority structure is Denia, needing long offshore transport that could significantly increase development costs.

4.2.3. *South-Western Spain region*

Three emission hubs are located in South-Western Spain region: E3, E11 and H4, with CO_2 emissions of 6.3, 2.3 and 2.3 Mtpa, respectively, accounting for 16% of the total emissions of all hubs. The main emitters with emissions higher than 1 Mtpa include a thermal power plant (Central Térmica Los Barrios – in decommissioning), two refinery enterprises (Refinería Gibraltar and Refinería La Rábida), and a pulp and paper enterprise (Complejo Industrial de Huelva). Very limited potential storage structures are found in this region. No more than five structures passed the screening process for these emission hubs, even when the source-to-sink distance was extended to 300 km. These three emission hubs share the same priority structure (Cádiz Arenoso). This structure has a high storage capacity and good reservoir-seal quality, which makes it suitable for CCS development. As alternative structures, Almonte has a relatively smaller storage capacity of less than 100 Mt compared to other potential structures. Moreover, its reservoir depth mainly ranges from 580 m to 850 m, and its suitability would need to be verified given a low CO_2 storage density in the gas phase, making the storage much less efficient than a supercritical setting.

4.2.4. *South-Eastern Spain region*

South-Eastern Spain region has two emission hubs in the power sector, E4 and E5, with CO_2 emissions of 6.3 and 3.2 Mtpa, accounting for 14% of the emissions of all hubs. The main emissions come from a thermal power plant emitting 6.3 Mtpa (Central Térmica Litoral de Almería – expected closure in 2021), which represents the third-largest emitter in Spain, and a refinery with emissions of 2.5 Mtpa (Repsol Petróleo Cartagena). There are also relatively limited potential storage structures in this region compared to NW and NE Spain. The E4 and E5 hubs share the same priority structure, Murcia B-1, which has high storage capacity and available seismic and well data that reduce the uncertainty of its storage suitability. In this region, the priority and alternative structures present relatively low porosity and permeability.

5. Discussion

5.1. *Priority CCS clusters and regions*

In this work, we have presented a general methodology and have applied it to show the feasibility and potential of CCS clusters in Spain. In the ALGECO2 project, 15 highly favourable and feasible structures were identified based on the suitability of storage structures and the quality of usable data [39] (Fig. 8A). In this study, we employed a source-to-sink assessment based on a hubs and clusters strategy to identify the prospective regions in Spain with the greatest CCS development potential, as a step forward from the available storage structure portfolio (Fig. 8B). This assessment takes into account three further factors: the spatial matching, i.e., the distribution of emission hubs and storage structures, the development cost, and the capacity matching, i.e., the priority storage should have enough capacity to store the 30-year emissions of the emission hub. This allows the identification of priority regions that ensure the longevity of prospective CCS projects and respond to Spain's long-term emission reduction target by 2050.

Emission hubs, rather than single emission facilities, were selected as CO_2 sources for the assessment. The adoption of emission hubs can ensure the availability of CO_2 sources and thus the longevity of prospective CCS projects necessary to achieve Spain's long-term target, in case some facilities within the emission hubs are shut down in the future. The assessment presented in this work could also serve to plan for the conversion or the creation of new clusters dedicated to blue hydrogen and BECCS, which rely on an early and extensive penetration of CCS (these options are explored in detail in section 5.2.2).

The main advantage of the hubs and clusters strategy is that it can help reduce the development cost of CCS deployment when multiple CO_2 emitters share infrastructure such as pipelines and storage complexes [20,105]. For example, in the hard-to-abate sector, only two industrial facilities have CO_2 emissions higher than 1.5 Mtpa in Spain, with the emissions of the rest ranging from 0.1 to 1 Mtpa. Compared to aiming for a single large project, a gradual development and build-out process may provide a more viable pathway in this sector. Note that small hard-to-abate emitters are distributed throughout the territory and could benefit from CCS infrastructure built for the identified clusters (see Fig. 6B). Previous research indicates smaller-scale industrial applications such as steel and cement works may benefit from CCS as much as power sector applications, but that sharing of infrastructure may be needed to make this economically viable [122].

Table 4
Detailed features of the priority and alternative storage structures for emission hubs. Data of priority structures obtained from ALGECO2 Database [68], Martínez del Olmo [40] and the Spanish Geophysical Information System [114].

Emission hubs				Priority storage structures											Alternative storage structures	
Sectors	Name	Emission (Mtpa)	90% of emission in 30 years (Mtpa)	Name	Capacity (Mt)	Reservoir effective thickness (m)	Reservoir porosity (%)	Reservoir permeability (mD)	Seal effective thickness (m)	Presence of natural fractures in seal	Reservoir middle depth (m)	Onshore distance to emission hub (offshore distance) (km)	Seismic	Well	First alternative structures	Second alternative structures
Power sector	E1	11.6	313.2	Mar Cantábrico J-1 S	270	140	12	n/a	1,000	n/a	1,320	217(3.5)	High 3D	0	Mar Cantábrico J-1P	Boñar
	E2	10.3	278.1	Iglesias (Utrillas)	678	135	14	10–100	1,344	low	1,845	190	High 2D	>5	Iglesias (Cretaceous)	Mar Cantábrico J-1 S
	E3	6.3	170.1	Cádiz Arenoso	>700	40–50	25	n/a	1,200	n/a	1,523	147 (10)	High 3D	3	Almonte	Cádiz Dolomítico
	E4	6.3	170.1	Murcia B-1	366	1,235	9	1–10	720	low	1,500	134	High 2D	2	Sierra Seca (Dogger-Lias)	Sierra de Salinas (Dogger)
	E5	3.2	86.4	Murcia B-1	366	1,235	9	1–10	720	low	1,500	95	High 2D	2	Sinclinal de Pétrola (Manuel sandstone)	Sierra Seca (Dogger-Lias)
	E6	3.1	83.7	La Zona de Enlace (Buntsandstein)	>500	162	13	100–1000	81	low	2,165	32	Low 2D	>5	Denia	Caspe-Mayals
	E7	2.8	75.6	Denia	>700	80	22	n/a	350	n/a	2,128	28 (1 9 2)	High 3D	0	La Zona de Enlace (Buntsandstein)	Barcelona-A
	E8	2.8	75.6	Barcelona-A	>500	150	8	n/a	600	n/a	2,432	29 (15)	High 3D	0	La Zona de Enlace (Buntsandstein)	Reus
	E9	2.3	62.1	Rioja Norte (pre- and *syn*-orogenic Tertiary)	>500	1,190	10	10–100	2,832	low	4,390	87	High 2D	>5	Iglesias (Utrillas)	San Pedro
	E10	2.1	56.7	Duero Centro-Meridional (Upper Cretaceous)	1,229	97	6.5	10–100	756	low	1,110	187	Low 2D	>5	Duero Centro-Meridional (Utrillas)	Boñar
	E11	2.0	54	Cádiz Arenoso	>700	40–50	25	n/a	1,200	n/a	1,523	21 (10)	High 3D	3	Almonte	Cádiz Dolomítico
Hard-to-abate sector	H1	7.1	191.7	Iglesias (Utrillas)	678	135	14	10–100	1,344	low	1,845	195	High 2D	>5	Iglesias (Cretaceous)	Mar Cantábrico J-1 S
	H2	4.2	113.4	La Zona de Enlace (Buntsandstein)	>500	162	13	100–1000	81	low	2,165	178	Low 2D	>5	Barcelona-A	Reus
	H3	2.3	62.1	La Zona de Enlace (Buntsandstein)	>500	162	13	100–1000	81	low	2,165	115	Low 2D	>5	Reus	Denia
	H4	2.3	62.1	Cádiz Arenoso	>700	40–50	25	n/a	1,200	n/a	1,523	23(10)	High 3D	3	Almonte	Cádiz Dolomítico

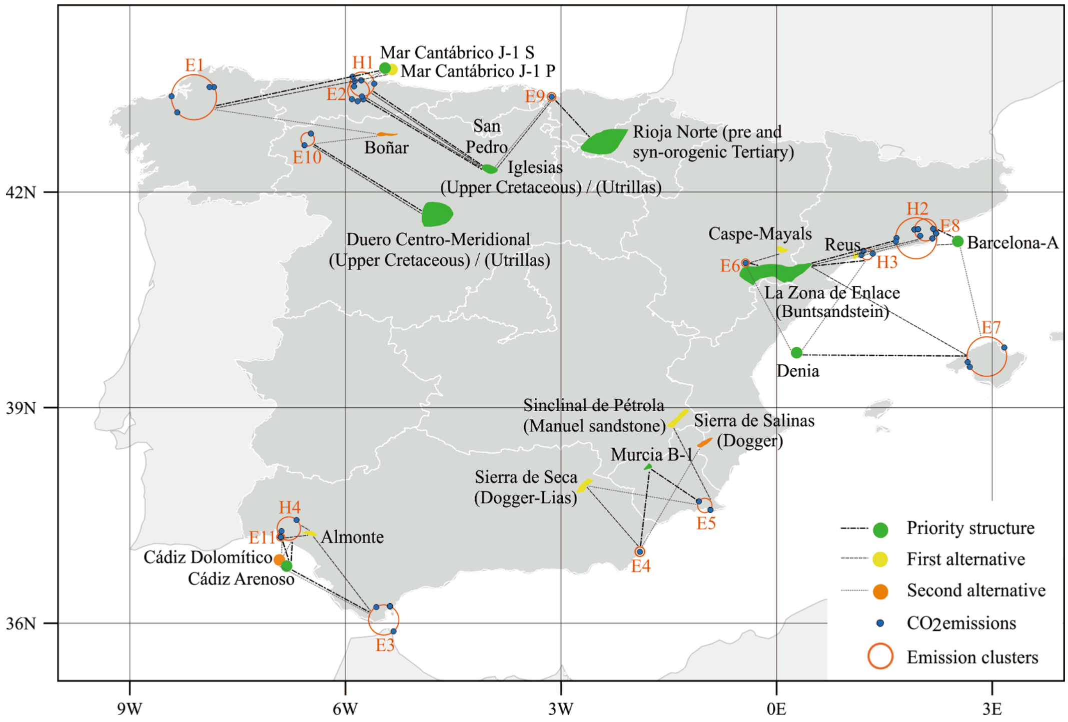

Fig. 7. The priority source-to-sink clusters and their alternative storage structures.

Priority source-to-sink clusters were identified using the methodology presented in Section 3.3. However, it should be noted that the availability of geological/geophysical data in most storage sites is very low, compared to other potential storage regions in Europe. For instance, there is a limited number of exploration wells in Spain (710 in total), compared to the 9,200 in France, 8,500 in Italy and 26,000 in the United Kingdom [40]. This is a result of the lack of hydrocarbon resources in Spain in comparison to similar sized countries. The lack of exploration data in Spain, particularly well data, imposes significant uncertainty on the suitability assessment of the storage sites, especially when trying to determine the injectivity (or maximum rate of injection) in the reservoir formation. Injectivity is a key parameter that determines the suitability of a storage site [123]. Unexpected low injectivity in a reservoir can dictate the fate of a CO_2 storage project, forcing its closure, examples being the In Salah project in Algeria [124] or the ZeroGen project in Australia [125]. Acquiring more geological data, particularly well data, to obtain better estimates of the injectivity is thus imperative in hydrocarbon-poor regions to reduce the uncertainty and thus increase the maturity of the storage sites.

Among the four potential CCS development regions, NW and NE Spain can be considered the priority regions in Spain. The emission hubs in the two regions have high total CO_2 emissions of 48.6 Mtpa, accounting for 71% of all selected emission hubs in Spain. Furthermore, they include emission hubs in both the power sector and the hard-to-abate sector, which can ensure the regions can play potential roles in different stages and scenarios of emission reduction. In this study, emission hubs are calculated from Spain's inventory of CO_2 emissions in 2018 [94]. Spain has a framework of emission reduction favourable to renewables resources and energy efficiency, and has established a plan to close coal-fired power plants. For example, three coal-based power plants included in this assessment (Central Térmica de Andorra in E6 hub and UPT Compostilla and Central Térmica de Anllares in E10 hub) have been recently closed, but they are included in our assessment because they were still included in the 2018 Spanish government inventory used as input for the emission data [94]. This is indicative of the rapid adaptation of the power sector to the use of sustainable energy sources. In contrast, in the hard-to-abate sector, the process-related emissions cannot be mitigated by other emission reduction approaches, and thus the potential of the source-to-sink clusters can be considered more predictable in the long term. Even in a scenario where Spain completely relies on renewable resources and energy efficiency to reduce emissions in the power sector, CCS in the hard-to-abate sector would still be necessary to achieve net-zero emissions in this sector [126].

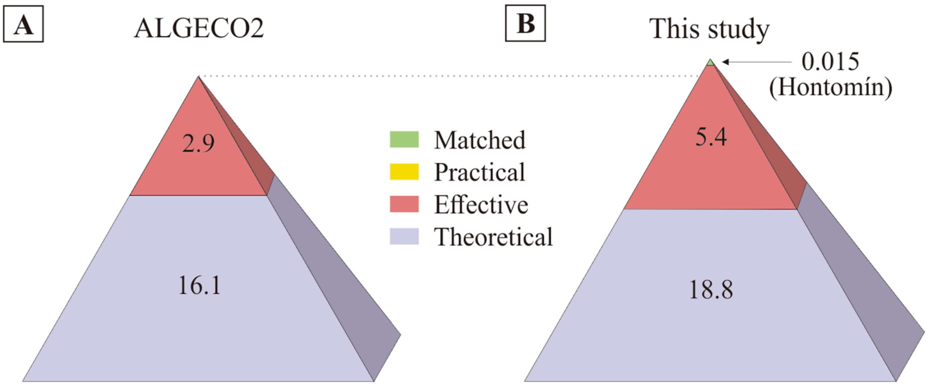

Fig. 8. Four-tier resource pyramid of Spain's CO_2 storage capacity (in Gt) framed by Carbon Sequestration Leadership Forum (CSLF) terminology after Cavanagh et al. [28] (see Fig. 1 for the description of the tiers). (A) Resource capacity outlined in the ALGECO2 project [68]. (B) Resulting from the source-sink matching process described in this study. The 5.4 Gt of effective capacity in (B) corresponds to the priority structures in Table 4 which have been assessed and assigned to priority emission hubs.

In NW and NE Spain, the main CO_2 emitters (≥1 Mtpa) in the hard-to-abate sector are an iron and steel enterprise in the H1 hub and two cement enterprises in the H2 and H3 hubs. These could mean long lasting, reliable emissions locations. Another two large CO_2 emitters of the hard-to-abate sector are in pulp and paper industry. In the cement industry, between 50% and two-thirds of the CO_2 emissions are process related, i.e., originating from the calcination of limestone where $CaCO_3$ is converted to CaO and CO_2 [127,128]. CCS is considered the method with the most potential for the overall reduction of the process-related emissions in the cement industry [128,129]. Cement plants possess several features favourable for CO_2 capture, e.g., high CO_2 concentration, few emission points and stable operation [130]. Based on a techno-economic analysis and systematic review of CCS in some industries [87], the cost of CCS in the cement industry is relatively lower than that in iron and steel industry and pulp and paper industry. Worldwide, there are two commercial CCS facilities in construction (Langskip CCS - Brevik in Norway) or development stages (LafargeHolcim CCS in the United States) and two pilot and demonstration facilities in operation or in construction in cement industry [19], indicating the feasibility of and interest in CCS deployment in this industry.

In addition to multiple emission hubs, NW and NE Spain contain more potential storage structures compared to SW and SE Spain (Fig. 4B and 7). The potential structures in NW Spain are mainly located in the Duero Basin and the Cantabrian Mountains. In NE Spain, the three priority and alternative onshore structures are Área de La Zona de Enlace (Buntsandstein), Reus and Caspe-Mayals, also identified as structures with high favourability in the ALGECO2 project [39]. In addition, two offshore potential structures, Barcelona-A and Denia, were also assessed as structures with very high suitability and very low risk by Martínez del Olmo [40]. The onshore structures are mainly distributed in the Ebro Basin and the Iberian Chain. Our analysis of the Ebro Basin is consistent with that of the STRATEGY CCUS project, which has recently selected the Ebro Basin as one of the three priority regions for large-scale deployment of CCS in Southern and Eastern Europe [131]. The Área de La Zona de Enlace (Buntsandstein) structure is shared by all emission hubs in NE Spain, and the Reus structure is shared by three emission hubs. These two structures present suitable reservoir-caprock systems and relatively low development cost since they are close to the emission hubs. They can be selected as potential candidates for further assessment to verify their suitability for CCS deployment. Our assessment results can be regarded as a reference for the selection of the most optimal storage sites for future CCS projects.

5.2. *CCS development strategy*

After establishing the feasibility and potential of CCS to decarbonise the power and industrial sectors in Spain, we now discuss the future of this technology in a broader, *trans*-national context. Although exercises to explore potential decarbonisation pathways envisage a significant role for CCS in different countries [6,82], most countries are yet to develop coherent strategies for its deployment due to various barriers, as discussed in the introduction section. Despite being the fifth highest GHG emitter in the EU, Spain is ranked eighth in the CCS Readiness Index database [132], which monitors the progress of CCS deployment by comprehensively considering a country's policy, law and storage resource development. There are no demonstration or commercial CCS projects planned in the near future in Spain, despite the great potential illustrated in this work. This is a clear indication that Spain's CCS development has stalled like in many other countries.

The CCS strategy proposed in this work involves a system of CCS hubs and clusters that could help to resolve this stagnation. This strategy is being progressively adopted in the North Sea region countries (e.g., Acorn in the UK [20] or Rotterdam in the Netherlands [133]) as well as other regions in the world [134]. Our approach has identified suitable priority options that can serve as First of a Kind CCS options in the different priority regions, as well as suitable alternatives that can be used for upscaling the CCS hubs. This can help to reduce costs via economies of scale and attract investment for build-out options [20,105,135]. Spain should explore this incremental strategy to promote the development of a CCS industry. In alignment with this incremental philosophy, two other factors must be considered to produce a holistic CCS-based strategy, the trans-national context and the integration with other clean energy technologies.

5.2.1. *Trans-national context*

The hubs and clusters identified in this work have been optimised for the decarbonisation of the Spanish industrial sectors. However, the battle against Climate Change is global, and the Spanish efforts are aligned with international directives and targets. Some of the source-to-sink clusters proposed in our case study lie close to border regions and could be of interest for industrial clusters in nearby countries. Thus, the strategy proposed needs to be put into a trans-national context.

Pipelines are considered to be the most viable method for onshore transport of high volumes of CO_2 over long distances [136], especially when the CO_2 source comes from a power or industrial plant with a long lifetime [16]. The challenge is to develop long-term strategies for CO_2 pipeline networks that optimise source-to-sink transmission [72]. For commercial-scale CCS projects, an extensive network of CO_2 pipelines needs to be developed, involving multiple CO_2 sources and storage sites. Due to an uneven distribution of CO_2 sources and potential storage structures, the construction of European pipeline infrastructures may become trans-national [137]. For the Iberian Peninsula, when Spain and Portugal are considered together in building a pipeline network, fewer hubs would be required, as well as less pipeline infrastructure and equipment, which would reduce costs for construction and installation [138]. Moreover, the existing natural gas pipeline network that connects Spain and Portugal can be used as a proxy when installing a future CO_2 pipeline network. Similarly, joint large-scale trans-national infrastructures have also been suggested in the western Mediterranean, including Spain, Portugal and Morocco [72]. In the western Mediterranean, most of the storage capacity is located in Spain [73,138,139] and, accordingly, Portugal and Morocco can benefit from gaining access to Spain's storage capacity by a trans-national pipeline network. Furthermore, Spain's pipeline network can also connect with a European network, as an EU-wide coordination of CO_2 transport planning, as well as the resolution of legal issues surrounding trans-boundary transport and liability, are essential to enable CCS in support of the EU targets [140]. The Connecting Europe Facility for Energy (CEF Energy), for example, is able to fund trans-national pipelines for CO_2 via Projects of Common Interest (e.g., this tool has already funded the CO2-SAPLING Transport and Infrastructure Project with this aim [141]). Vessel transport may complement pipeline networks in the western Mediterranean in some cases, achieving the transport of small CO_2 volumes over long distances, e.g., accessing the large CO_2 storage capacity in the North Sea [142].

5.2.2. *Integration with clean energy technologies: Blue hydrogen and BECCS*

This study shows that CCS has the potential to contribute significantly to the decarbonisation of Spain by storing CO_2 emissions from both the power sector and the hard-to-abate sector. Additionally, CCS can also be combined with low-carbon or carbon–neutral technologies to generate net-zero or even negative emissions [4], e.g., the implementation of blue hydrogen production as well as BECCS, two technologies with the potential to push forward the energy transition towards a zero-carbon society and with potential for alleviating the related costs [143].

Hydrogen can be adopted as a key energy carrier [144–146], which is an energy vector that tackles security of energy supply, ideally with net-zero emissions, and hence can decarbonise energy sectors such as energy intensive industries, heating and transport [147,148]. Renewable production of hydrogen ('green hydrogen') relies on either biomass processing or water splitting, the latter divided into electrolysis, thermolysis and photo-electrolysis technologies [149]. Machhammer et al. [150] compared the cost and carbon footprint related to hydrogen production technologies and identified several Pareto-efficient technologies: water electrolysis using wind power (zero carbon footprint for operation; high cost), methane pyrolysis (medium carbon footprint; medium cost) and conventional methane steam reforming (SMR) (high carbon footprint; low cost). Hydrogen from methane steam reforming in combination with CCS ('blue hydrogen') can provide a low-cost route with low carbon footprint to the decarbonisation of heating as well as support the development of other aspects of the hydrogen economy including the use of fuel cells [4]. The large-scale generation of hydrogen using steam methane reformation is only sustainable if supported by CCS, because CO_2 is a by-product of the methane reforming process and needs to be stored permanently in large quantities. The abundance of CO_2 storage potential close to industry hubs could make hydrogen production using SMR a suitable low-carbon energy option for Spain. The deployment of blue hydrogen will be a part of a transitional phase during which the installation of a fully sustainable hydrogen infrastructure, such as large-scale electrolysers, is implemented, in line with the EU hydrogen strategy [151]. Therefore, the application of CCS will support Spain's transition to meet the targets of the Spanish Green Hydrogen Roadmap [152], which envisages ambitious targets, i.e., 4 GW electrolysers installed capacity by 2030 and at least 25% with green hydrogen, in response to the EU hydrogen strategy [151]. Blue hydrogen could be a bridging technology to reach these targets in the medium term [10].

Achieving global net zero CO_2 emission targets will also likely require NET to offset the unavoidable release of anthropogenic greenhouse gases [153]. BECCS is a NET that combines bioenergy applications with CCS. Biomass binds CO_2 from the atmosphere as it grows and, if captured and stored in geological formations after conversion, results in a net removal of CO_2 from the atmosphere [4]. Despite important criticisms towards its deployment at the scale needed, BECCS is regarded as a key tool for achieving decarbonisation targets [12,13,154]. BECCS could be not only a zero carbon power source, but help to counteract the effect of dispersed or fugitive emissions [155], such as those from the transport sector, which is the major source of CO_2 emissions in Spain (Fig. 3). A relevant issue in the feasibility of large-scale deployment of BECCS is the availability of biomass feedstocks and land for production. Competition between different sectors for feedstocks and competition with other ecosystem services are limiting factors for BECCS as a large-scale NET, since land demand for BECCS is relatively high and largely depends on the selected feedstocks [153,156]. Coupling land-use-energy of different technologies in integrated assessment models (IAMs) indicates a competition for resources, in particular a need to address land used challenges, i.e., mitigation and adaptation to climate change, desertification and land degradation, and food security [157]. Further work should focus on evaluating how much sustainable BECCS can be produced in Spain, considering all these issues.

Spain's long-term decarbonisation strategy neither explicitly dismisses nor endorses BECCS, echoing the debate around assessing and supporting best practices that would strike a right balance between competing agents such as food and energy security, climate change, land challenges, and water stresses. However, Spain's CO_2 storage potential makes BECCS a realistic opportunity to meet future emission targets. BECCS also has the potential of enabling a just transition of the power sector and the creation of new technology-based jobs, that help to ease the evolution into a more sustainable industry model [155,158].

6. Conclusions

To achieve the Paris Agreement's long-term emission reduction target, i.e., achieving net-zero CO_2 emissions by 2050, all countries need to take serious decarbonisation actions, and CCS is an integral technology to achieve this. CCS clusters with their associated hubs will be essential to decarbonise intensive industries and enable sustainable economic development. Selecting the most suitable hubs and clusters is therefore key to identify opportunities for investment and development.

We presented an integrated source-to-sink analysis tool based on a comprehensive analysis of CO_2 emission hubs, the suitability of storage structures, and the matching of sources and sinks, including Multi-Criteria Decision Analysis tools, which reveals the potential of CCS development in our case study in Spain. This workflow identified 15 priority source-to-sink clusters and four high-potential CCS development regions were identified, located in the four corners of the country. To ensure the reliability of prospective CCS projects, development areas should be selected in the regions with multiple storage structures and emissions, which will persist into decades ahead, preferably from both the power and the hard-to-abate sectors. NW and NE Spain can be considered the two priority regions for CCS development, followed by the SW and SE regions. The source-to-sink clusters in the priority regions, especially where storage structures are shared by multiple emission hubs, deserve further research and could become the prioritised options for future pilot and demonstration projects.

Many countries (e.g., Spain, UK, Germany, Japan or Korea) made promising starts on CCS in the late 2000 s, but its deployment has been stagnant partly due to a lack of political and financial support. The proposed hubs and clusters strategy could attract renewed public and political interest in this technology. The current global energy decarbonisation strategy is favourable to the switch towards renewable energy resources, where CCS can have a secondary (and short-to-middle term) decarbonisation role. However, CCS in the hard-to-abate sector will still be necessary to deal with the process-related emissions. CO_2 emitters in this sector with relatively low development cost can be priority sources for CCS development, e.g., in the cement industry. Apart from being integrated into existing energy systems and emission-intensive industries, there is significant potential for combining CCS with blue hydrogen generation and bioenergy, other low-carbon energies that can greatly contribute to achieving the Paris Agreement's net-zero target.

CRediT authorship contribution statement

Xiaolong Sun: Data curation, Formal analysis, Methodology. **Juan Alcalde:** Conceptualization, Methodology, Validation. **Mahdi Bakhtbidar:** Data curation, Formal analysis. **Javier Elío:** Data curation, Formal analysis. **Víctor Vilarrasa:** . **Jacobo Canal:** . **Julio Ballesteros:** . **Niklas Heinemann:** . **Stuart Haszeldine:** . **Andrew Cavanagh:** . **David Vega-Maza:** . **Fernando Rubiera:** . **Roberto Martínez-Orio:** . **Gareth Johnson:** . **Ramon Carbonell:** . **Ignacio Marzan:** Validation. **Anna Travé:** . **Enrique Gomez-Rivas:** Validation.

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.

Acknowledgements

Funding was provided by the Grup Consolidat de Recerca "Geologia Sedimentària" (2017SGR-824) and the DGICYT Spanish Project PGC2018-093903-B-C22. XS acknowledges funding by the China Scholarship Council for a PhD scholarship (201806450043). JA is funded by MICINN (Juan de la Cierva fellowship - IJC2018-036074-I). EGR acknowledges funding provided by MICINN ("Ramón y Cajal" fellowship RYC2018-026335-I). VV acknowledges funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program through the Starting Grant GEoREST (www.georest.eu) (Grant agreement No. 801809). IDAEA-CSIC is a Centre of Excellence Severo Ochoa (Spanish Ministry of Science and Innovation, Project CEX2018-000794-S). NH is funded by the Engineering and Physical Sciences Research Council (EPSRC) funded research project "HyStorPor" (EP/S027815/1). SH and AC are funded by EPSRC EP/P026214/1 UKCCSRC 2017, and EU project 837754 - STRATEGY CCUS. DVM is funded by the Spanish Ministry of Science, Innovation and Universities ("Beatriz Galindo Senior" fellowship BEAGAL18/00259). GJ is funded by the University of Strathclyde Faculty of Engineering.

Table A1
Non-exhaustive list of projects related to CCS lead or participated by Spanish institutions

Topic	Acronym	Full name	Funding body	Date (start–end years)	References or Links
Capture	ECO-Scrub	Enhanced capture with oxygen for scrubbing of CO_2	RFCS	2007–2010	https://op.europa.eu/en/publication-detail/-/publication/293a59ae-700a-475b-83ad-2f98514278ad
Capture	ECLAIR	Emission free chemical looping coal combustion process	RFCS	2008–2012	https://op.europa.eu/en/publication-detail/-/publication/c971f36e-fa56-4c0a-9053-b8fd9100a06e
Capture	CaOling	Development of postcombustion CO_2 capture with CaO in a large testing facility	FP7	2009–2013	https://cordis.europa.eu/project/id/241302
Capture	FECUNDUS	Advanced concepts and process schemes for CO_2 free fluidised and entrained bed co-gasification of coals	RFCS	2010–2013	https://op.europa.eu/en/publication-detail/-/publication/5683e484-ef5d-11e6-8a35-01aa75ed71a1
Capture	ReCal	Novel calcium looping CO_2 capture process incorporating sorbent reactivation by recarbonation	RFCS	2012–2015	https://op.europa.eu/en/publication-detail/-/publication/f24545b2-9c46-11e8-a408-01aa75ed71a1
Capture	ASC2	Amine-impregnated solid sorbent for CO_2 capture	RFCS	2013–2017	https://op.europa.eu/en/publication-detail/-/publication/7d2d8212-9c72-11e9-9d01-01aa75ed71a1
Capture	SUCCESS	Scale-up of oxygen carrier for Chemical Looping Combustion using environmentally sustainable materials	FP7	2013–2017	https://clc-success.project.tuwien.ac.at/home/
Capture	CaO2	Calcium looping CO_2 capture technology with extreme oxy-coal combustion conditions in the calciner	RFCS	2014–2017	https://op.europa.eu/en/publication-detail/-/publication/08a126e1-9d3f-11e9-9d01-01aa75ed71a1
Capture	HiPerCap	High Performance Capture	FP7	2014–2017	https://cordis.europa.eu/project/id/608555
Capture	ASCENT	Advanced Solid Cycles with Efficient Novel Technologies	FP7	2014–2018	https://cordis.europa.eu/project/id/608512
Capture	CEMCAP	CO2 capture from cement production	H2020	2015–2018	https://www.sintef.no/projectweb/cemcap/
Capture	FlexiCaL	Development of flexible coal power plants with CO2 capture by Calcium Looping	RFCS	2016–2019	https://www.flexical.eu/
Capture	GRAMOFON	New process for efficient CO_2 capture by innovative adsorbents based on modified graphene aerogels and MOF materials	H2020	2016–2020	http://www.gramofonproject.eu/
Capture	FLEDGED	FLExible Dimethyl ether production from biomass Gasification with sorption-enhancED processes	H2020	2016–2020	https://cordis.europa.eu/project/id/727600/es
Capture	Cleanker	CLEAN clinKER production by calcium looping process	H2020	2017–2021	http://www.cleanker.eu/
Capture	CLARA	Chemical looping gasification for sustainable production of biofuels	H2020	2018–2022	https://cordis.europa.eu/project/id/817841/es
Capture	C4U	Advanced Carbon Capture for steel industries integrated in CCUS Clusters	H2020	2020–2024	https://c4u-project.eu/
Capture	GLAMOUR	GLycerol to Aviation and Marine prOducts with sUstainable Recycling	H2020	2020–2024	https://cordis.europa.eu/project/id/884197/es
Capture and usage	CENIT SOST CO_2	Nuevas Utilizaciones industriales Sostenibles del CO_2	Spanish Government – Private funding	2008–2011	https://www.ecestaticos.com/file/6292f8da3aec91e6df801b68eaf14be2/1394023865.pdf
Storage	CARBOLAB	Improving the knowledge of carbon storage and coal bed methane production by “in situ” underground tests	RFCS	2009–2013	https://op.europa.eu/en/publication-detail/-/publication/1ce238a4-f1dd-4b52-987f-005ef562f173
Storage	MUSTANG	A multiple space and time scale approach for the quantification of deep saline formations for CO2 storage	FP7	2009–2014	https://cordis.europa.eu/project/id/227286
Storage	PANACEA	Predicting and monitoring the long-term behavior of CO_2 injected in deep geological formations	FP7	2012–2014	http://www.panacea-co2.org/
Storage	TRUST	High resolution monitoring, real time visualization and reliable modeling of highly controlled, intermediate and up-scalable size pilot injection tests of underground storage of CO2	FP7	2012–2017	http://www.trust-co2.org/
Storage	ENOS	ENabling Onshore CO2 Storage in Europe	H2020	2016–2020	http://www.enos-project.eu/
Storage	PCROCKSS	Interacción cemento Portland – roca en medios ácidos: secuestro geológico del CO2 y gestión de residuos de minas de sulfuros	Spanish Government	2018–2020	https://www.idaea.csic.es/project/pcrockss/
Storage	GEoREST	Predicting earthquakes induced by fluid injection	H2020ERC-STG	2019–2024	https://www.georest.eu/
Storage	HydroPore	A new upscaling approach for multiphase flow, mechanical deformation, and hydrodynamic transport in permeable media	Spanish Government	2020–2023	http://hydropore.es/
Full CCS chain	OXYCFB300 Compostilla	OXYCFB300 Compostilla Carbon Capture and Storage Demonstration Project	EEPR	2009–2012	https://www.globalccsinstitute.com/archive/hub/publications/137158/Compostilla-project-OXYCFB300-carbon-capture-storage-demonstration-project-knowledge-sharing-FEED-report.pdf
Full CCS chain	ECCSEL	European Carbon Dioxide Capture and Storage Laboratory Infrastructure	H2020	2015–2017	http://www.eccsel.org/
Full CCS chain	ACT	Accelerating CCS technologies as a new low-carbon energy vector	H2020	2016–2021	http://www.act-ccs.eu/

Appendix A

Table A1.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117418.

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