CARBON REMOVAL READINESS ASSESSMENT

Spain's potential to deploy CDR at scale and speed

Background report

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A collaboration between

carbon gap

globalfactor

About the Carbon Removal Readiness Assessment project

Many governments have already committed to net zero. Moreover, the IPCC forecasts the need for hundreds of billions of tonnes of CDR to stabilise global temperatures well below 2°C. Yet, few, if any, governments currently have a robust plan in place to develop and deploy atmospheric carbon dioxide removal (CDR) at the capacity required to counteract remaining emissions at the point of net zero. Most CDR forecasts are on a global scale, failing to inform CDR planning and policy design at the country level. Data is also lacking to determine what is achievable at the level of each country.

Inspired by the Renewables Readiness Assessments published by the International Renewable Energy Agency, our Carbon Removal Readiness Assessments (CRRA) aims to fill this information gap to support national policymakers in complementing their climate strategies with ambitious yet realistic CDR goals. The CRRA aim to estimate the potential for CDR deployment at a country level and produce country-specific roadmaps with local stakeholders to assist decision-makers in understanding the opportunities and the actions needed to realise them.

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Disclaimer

This document presents a quantified estimate of Spain's potential for the deployment of CDR methods. As most of the methods assessed in this report are still in the early stages of development, the assessment includes significant uncertainties: some methods may not prove viable, while others that are excluded in this report may develop quicker than expected.

CDR still being a relatively new topic, accurate and reliable data from official sources are not always available. Key gaps include detailed mapping of geological storage, integration of land and marine resources, and regional assessment of co-benefits and trade-offs. For methods such as OAE or large-scale mineralisation, the lack of field data prevents robust estimates. Uncertainties in biomass supply, soil carbon dynamics, and ecosystem sink stability further limit accuracy. In addition, the absence of harmonised monitoring and reporting frameworks reduces comparability and policy relevance. Consequently, the analysis in this report involves assumptions made by the project team to estimate the deployment potential. These are reported transparently along the text.

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Executive summary

In its Sixth Assessment Report (AR6, 2022), the IPCC estimated that reaching and sustaining net zero to achieve the Paris Agreement's climate goals would require multiple (~5 to 10) gigatonnes of CO_2 removed from the atmosphere every year by 2050. Further delays in cutting emissions have since then contributed to exhaust the remaining carbon budget faster than expected. As a result, the world will soon enter overshoot, strengthening the need for large scale carbon dioxide removal (CDR).

Europe, along with other large historical emitters and developed economies, has a particular role to play in scaling CDR, combining responsibility and capacity to do it. In this context, Spain emerges as a distinct case as the country is deemed to hold the largest CDR potential in Europe. Yet Spain is also amongst the least advanced countries in developing CDR projects as well as putting in place a suitable policy mix.

This report provides initial quantified insights into Spain's potential to deploy CDR to support the country quickly progressing towards an ambitious yet responsible CDR strategy. Grounded in a bottom-up analysis of Spain's available resources, this study estimates both theoretical and realistic potentials for implementing various CDR methods through 2050. Recognising that CDR deployment is not solely a technical challenge, the report also analyses the 'social geography' around CDR – capturing stakeholder perspectives, including those of the public through a citizen panel discussion.

The assessment follows six key steps:

1. Identification and selection of relevant CDR methods;
2. Mapping of available resources for CDR, including renewable electricity, waste heat, biomass, land, water, and geological storage capacity, among others;
3. Estimation of the maximum theoretical CDR potential;
4. Evaluation of Spain's regulatory, economic, and political landscape;
5. Analysis of societal attitudes toward CDR deployment in Spain, based on stakeholder interviews and a citizen panel;
6. Estimation of realistic CDR potential for 2050 based on three scenarios.

Main results on Spain's CDR potentials

The report reviews a range of CDR methods – grouped into ecosystem management, biomass conversion, geochemical, and synthetic approaches – and assesses their respective theoretical and realistic potentials based on Spain's available resources. This comprehensive evaluation leads to a **theoretical maximum CDR potential of ~196 Mt CO_2** per year by 2050, assuming that all available physical and natural resources were fully dedicated to CDR purposes after discounting for priority uses as described in section 4.1. Such a level of resource mobilisation would not be attainable under real-world conditions but provides a benchmark for understanding Spain's technical capacity to remove carbon. The theoretical potential is dominated by ecosystem-based methods, particularly afforestation/reforestation (~50.24 Mt CO_2) and improved forest management (~31 Mt CO_2), which together represent more than half of the total.

To assess Spain's **realistic capacity for CDR deployment**, three scenarios were developed: Conservative, Reference, and Ambitious (Figure 1). The three scenarios primarily differ in the pace of technological development, the availability of renewable energy, and the degree of institutional support and social acceptance.

The **Conservative scenario** assumes slow technological uptake and limited financial and policy support. Deployment remains restricted to voluntary initiatives, reforestation, and biochar production, constrained by limited financing, low social awareness, and the absence of large-scale CO_2 storage infrastructure. The Conservative scenario achieves nearly **~17 Mt CO_2** per year by 2050, a level insufficient to meet Spain's carbon-neutrality target, even with the projected natural sink of 9 MtCO_2/year.

The **Reference scenario** assumes moderate policy incentives and gradual improvements in land management and renewable energy availability, allowing partial integration of BECCS and DACCS facilities linked to existing industrial clusters, yet still hindered by regulatory uncertainty and competition for land and biomass. The Reference scenario achieves **~52 Mt CO_2** removed per year by 2050. This would close Spain's 2050 residual emissions gap of 29 Mt of CO_2 identified in the Long-Term Decarbonisation Strategy,[1] which also projects natural sinks absorbing 37 $MtCO_2e$[a] by that date, thereby achieving net negative emissions.

The **Ambitious scenario** envisions strong political commitment, early public investment in CO_2 transport and storage networks, clear certification mechanisms under the forthcoming EU Carbon Removal Certification Framework, and broad social acceptance. In this context, CDR deployment reaches a significant scale, attaining nearly **~69 Mt CO_2** removed per year by 2050, which would allow Spain to be net-negative by a large extent.

Across all scenarios, ecosystem management methods account for more than 70% of Spain's realistic removal capacity by mid-century, making them the greatest contributors to overall CDR potential. In addition to CDR methods, natural sink absorption has been included to take into account absorptions that, although not additional, would also contribute to net-zero emissions targets. The values obtained for natural sinks come from estimates of absorption by natural ecosystems, excluding CDR.

The most recurrent limiting factors for deploying CDR are the scarcity of characterised geological storage, fragmented governance, limited MRV standardisation, and high operational costs of synthetic methods, all of which must be addressed to enable long-term scalability.

Carbon Gap's CARE calculator indicates that, depending on the scenarios (reflecting negotiations within and beyond the EU), **Spain should aim for a CDR capacity of 137 to more than 350 $MtCO_2$/year by mid-century**. Understanding how much of that capacity can be realised is therefore essential.

Key takeaways

1. **The realistic CDR potential in Spain shows that CDR could make a meaningful contribution to Spain's climate targets.** By 2050, both the Reference and Ambitious scenarios reveal CDR volumes that could enable net-zero within the expected residual emissions estimated by the National Integrated Energy and Climate Plan (NIEP) and may allow Spain to go net negative.

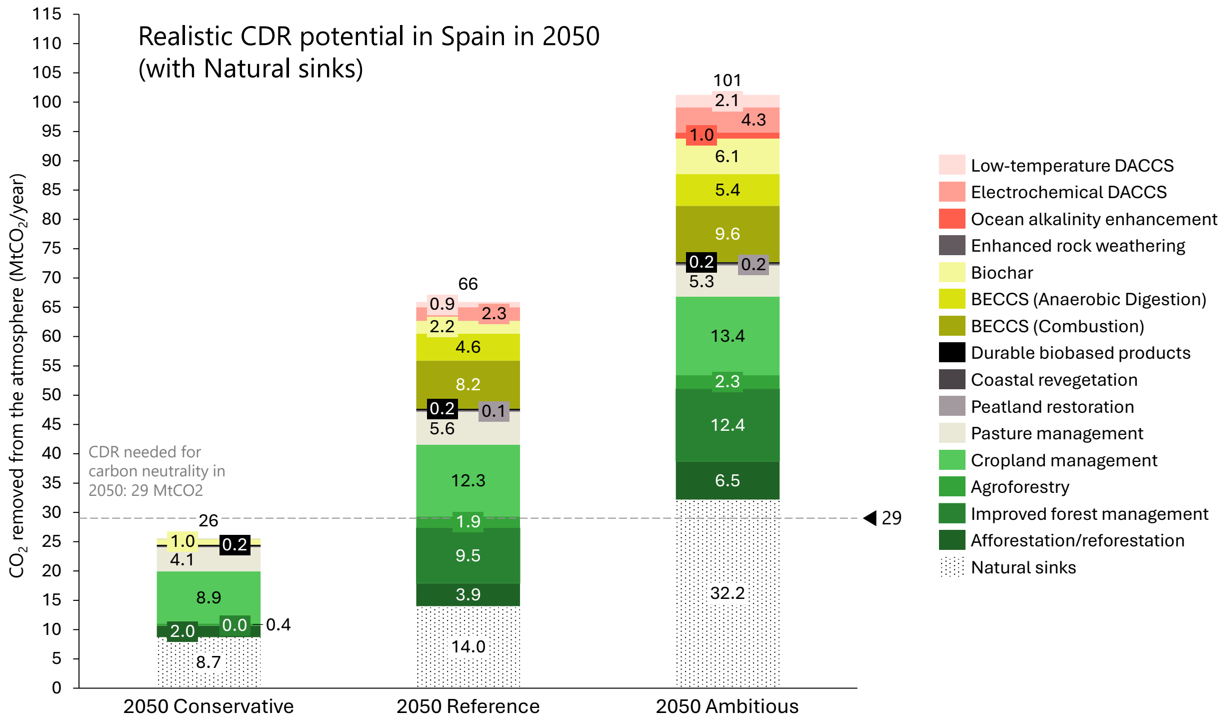

Figure 1. Spain's realistic CDR potentials across Conservative, Reference and Ambitious scenarios in 2050.

a. Because the official projections don't separate deliberate CDR from natural uptake, this study estimated the land available for the CDR methods considered, calculated their potential absorption, and subtracted it from the 37 $MtCO_2$ to determine the remaining "natural" sink.

2. **Geological storage capacity is the critical bottleneck for DACCS and BECCS in Spain.** Storage sites remain poorly characterised, and no dedicated CO_2 transport infrastructure exists. Without an accelerated, large-scale industrial policy to expand and align storage and transport with capture potential, deployment will remain constrained. Competition with CCS projects for both capacity and infrastructure further reduces availability, undermining secure and scalable carbon removal.

3. **The absence of national governance and policy frameworks on CDR slows the development of a coherent CDR strategy and the development of CO_2 storage infrastructure.** This lack of clarity delays investment decisions and complicates permitting processes, creating a significant barrier to advancing carbon removal at scale. Accelerated geological assessments, infrastructure build-out, and coordinated long-term planning are needed to unlock Spain's ability to deploy CDR at scale.

4. **Most CDR methods are possible in Spain.** Mobilising a diversified portfolio of CDR methods distributes risk and resource pressure. It also provides flexibility to offtake markets and governance structures. However, a diversified CDR portfolio requires significant coordination between the central government, the regions and industry to ensure that all potential methods are developed to their full potential.

5. **Spain is expected to increase its carbon-sequestration capacity through greater forest cover and more sustainable agricultural practices.** Spain is moving toward more sustainable land use, with a moderate reduction in agricultural land and a forest expansion that could reach 18.4–19.1 Mha by 2050. Unmanaged forest areas and non-wooded land offer high potential for reforestation and restoration for CDR purposes. The potential from agriculture will be smaller but more resilient, with strong potential for implementing CDR methods. Grasslands may decline to 11.1–12.4 Mha, partly transitioning into forests. However, wildfire risk and competition from land use may increase the risk of reversal and the capture potential of the natural sink.

6. **Spain's climate framework faces uneven implementation and a lack of incentives, coordination, and public awareness.** Stakeholders broadly view nature-based solutions as the most viable in the short term, and public support is strongest for ecosystem-based CDR methods such as reforestation, soil carbon sequestration, and biochar. Acceptance is moderate for geochemical methods and low for technological or marine-based methods, though it increases when projects deliver visible local co-benefits like biodiversity gains or rural employment. Technological methods remain promising but are still constrained by cost, technological maturity, and regulatory gaps. Moving forward, Spain needs a national strategy that integrates natural and technological CDR solutions, backed by science, investment, and strong public-private collaboration.

The realistic CDR potential scenarios presented in this report should not be interpreted as forecasts, but as illustrative pathways. Although all three realistic scenarios should be feasible, the actual level of CDR achieved in Spain by 2030, 2040 and 2050 will depend on levels of public and private investment, strategic choices, social acceptance and the evolution of relevant markets.

The concrete actions required to Spain's CDR potential are outlined in a separate *Roadmap* that builds on the findings of this background report.

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List of abbreviations

BAU	Business as usual
bcm	Billion cubic meters
BECCS	Bioenergy with carbon capture and storage
CAPEX	Capital expenses
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CDR	Carbon dioxide removal
CHP	Combined heat and power
CL	Carbon Limits
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Conference of the Parties
CRCF	Carbon Removal Certification Framework
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DOCCS	Direct ocean carbon capture and storage
EEA	European Environmental Agency
EEZ	European Economic Zone
ESR	Effort Sharing Regulation
ETS	Emission Trading System
EU	European Union
EUR	Euro (€)
GDP	Gross domestic product
GHG	Greenhouse gases
Gt	Giga-tonne
GW	Gigawatts
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
km	Kilometre
km^2	Square kilometres
Kt	Kilotonne
kV	Kilo-Volt
LCA	Life cycle assessment
LULUCF	Land use, land use change, and forestry
m^3	Cubic meters
mcm	Million cubic meters
mm	Milli-meter
MRV	Monitoring, reporting, and verification
Mt	Million tonnes
$MtCO_2$	million tonnes of carbon dioxide
MTK	The Central Union of Agricultural Producers and Forest Owners
Mtpa	Million tonnes per annum
MW	Megawatts
NATO	North Atlantic Treaty Organization
NDC	Nationally determined contribution
NIEP	National Integrated Energy and Climate Plan
NTC	Net Transfer Capacity
OAE	Ocean alkalinity enhancement
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational expenses
pH	Potential of Hydrogen
QGIS	Quantum Geographic Information System
R&D&I / RDI	Research, development and innovation
S-DAC	Solid sorbent direct air capture
SMR	Small modular reactors
SRL	Storage readiness level
t	Tonnes (metric)
TRL	Technology readiness level
TSO	Transmission system operator
TWh	Terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar ($)
VCM	Voluntary carbon market
WEM	With Existing Measures

1. Introduction

Climate change is one of the most significant challenges of the 21st century, endangering ecosystems, human health, economies, and global security. In response, the 2015 Paris Agreement committed signatories to

> *Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.*[2]

Meeting these targets requires not only rapid and deep emissions reductions across all sectors, but also the removal of carbon dioxide (CO_2) from the atmosphere to offset residual emissions With a 70% likelihood that the 1.5°C threshold will be temporarily exceeded between 2025 and 2029[3], CDR is increasingly viewed as a critical tool—not just for balancing emissions, but for actively reversing temperature overshoot. Its role will be essential throughout the remainder of this century to help bring global temperatures back within safe limits.

CDR refers to anthropogenic processes used to remove CO_2 from the atmosphere and store it to prevent further warming. CDR is not an alternative to emissions reductions, but it is a necessary addition, particularly in hard-to-decarbonise industries such as agriculture, aviation, and heavy industry[4] CDR methods range from biological and nature-based solutions to technological processes that physically and chemically separate CO_2 directly from the air and store it durably in underground geological formations.

Despite growing recognition, CDR faces significant uncertainties around technical maturity, economic feasibility, environmental risks, and public acceptance. Country-specific assessments are crucial for tailoring solutions to local socio-economic and geographical contexts, thereby enhancing the feasibility and effectiveness of these solutions.

The European Union (EU) has committed to achieving greenhouse gas (GHG) neutrality by 2050 and net-negative thereafter[3] and as a member state, Spain must chart its own path toward this goal. The country is already facing destructive floods, record heatwaves, and increasingly severe wildfires, while parts of the east risk shifting toward semi arid or desert like conditions. These impacts threaten communities, agriculture, and long term water security. Against this backdrop, stronger climate action isn't just about meeting EU obligations - it's a matter of national self preservation. Every step Spain takes to cut emissions, build resilience, and support broader European climate efforts directly protects its own communities, landscapes, and long term prosperity.

Spain was selected for the Carbon Removal Readiness Assessment (CRRA) project due to its substantial theoretical CDR potential[5,6], its early-stage national dialogue on the topic, and the need for tailored strategies that reflect its distinct socio-economic and geographic conditions.

This report addresses a critical gap in the literature by evaluating Spain's readiness for CDR, mapping existing capacities, barriers, and opportunities. It offers actionable insights for policy makers, multidisciplinary researchers, and stakeholders aspiring to integrate CDR within national climate strategies – advancing Spain's contribution to global climate goals and sustainable development.

This report was prepared using a bottom-up approach, which included desk research, interviews with relevant national stakeholders, and public engagement through a citizen panel.

The following Chapter 2 outlines the various CDR methods available, and the ones selected for this study. Chapter 3 then describes Spain's geographical landscape, including current and prospective resources and feedstocks necessary to deploy CDR. In Chapter 4, a preliminary estimation of CDR potential is presented based only on the physical resources – the so-called "theoretical" potential. Following this, Chapters 5 and 6 outline Spain's social geography by analysing the socio-economic, regulatory, and political landscape to describe the results of the stakeholder interviews and citizen panel. Finally, Chapter 7 presents the estimation of CDR potential across various scenarios, taking into account the results of both physical and social geography. The report concludes with targeted recommendations for policymakers, researchers, and stakeholders, aimed at integrating CDR into national climate strategies and advancing Spain's contribution to global climate goals.

2. CDR pathways and their resource requirements

This report's definition of CDR follows three key principles:

1. The CO_2 captured must come from the atmosphere (or oceans), not from fossil sources;

2. The subsequent storage must be durable over climate-relevant timescales (typically decades to centuries or millennia), in either geological, terrestrial, oceanic, or durable products.

3. The removal must be the result of human intervention, additional to the Earth's natural carbon cycling[7].

It is important to clearly distinguish CDR from other related concepts, such as carbon capture and utilisation (CCU) and carbon capture and storage (CCS). While CCU and CCS share some components with certain CDR methods, they do not necessarily result in durable net removal of CO_2 from the atmosphere, as illustrated in Figure 2.

2.1 Diversity of CDR methods

CDR methods are essential to neutralise residual emissions from hard-to-abate sectors and to achieve long-term climate stabilisation. Their effectiveness depends not only on the amount of CO_2 removed but also on the durability of storage, scalability, and social acceptability.

CDR methods can be classified into four main categories: enhanced ecosystem management, biomass conversion/preservation, geochemical carbon removal, and synthetic carbon removal, as shown in Figure 3. A short description of each CDR method is provided in the following sections.

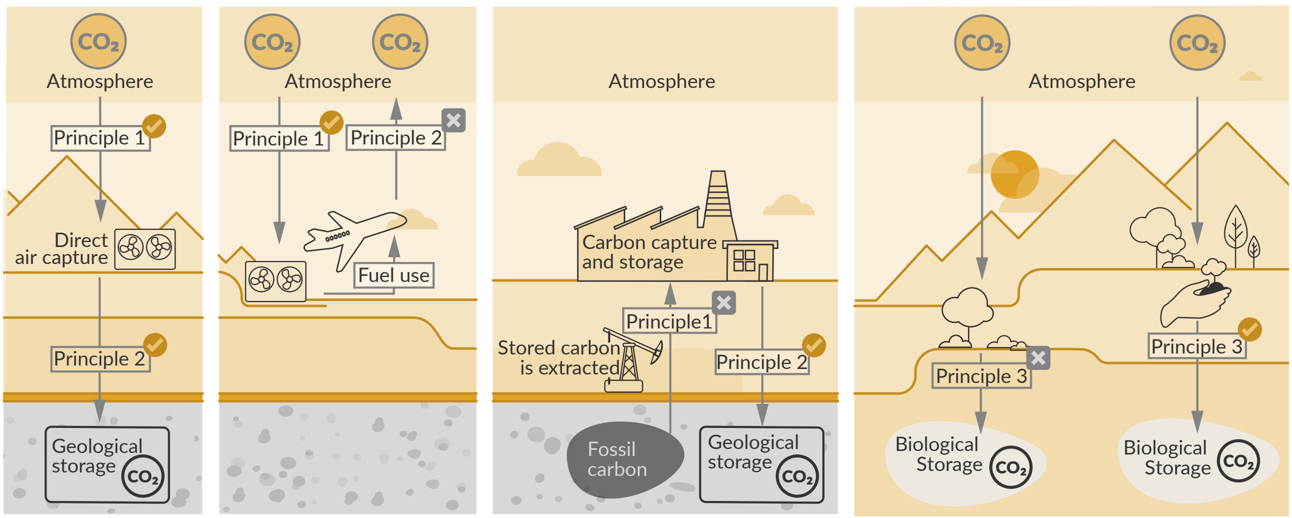


Figure 2. Differences between CDR, CCU, CCS, and natural carbon sink processes. Image A illustrates direct air capture (DAC) with permanent geological storage, a configuration that satisfies all three core principles of carbon dioxide removal. In contrast, Image B depicts DAC where the captured CO_2 is used in short-lived products such as fuels, thereby failing to meet Principle 2 on durability. Image C shows the capture and geological storage of fossil-derived CO_2, which does not meet Principle 1, as it does not remove carbon already in the atmosphere. Image D presents natural processes like tree growth, which fall short of Principle 3 unless actively enhanced through human intervention (Figure from the State of CDR report, 2024).

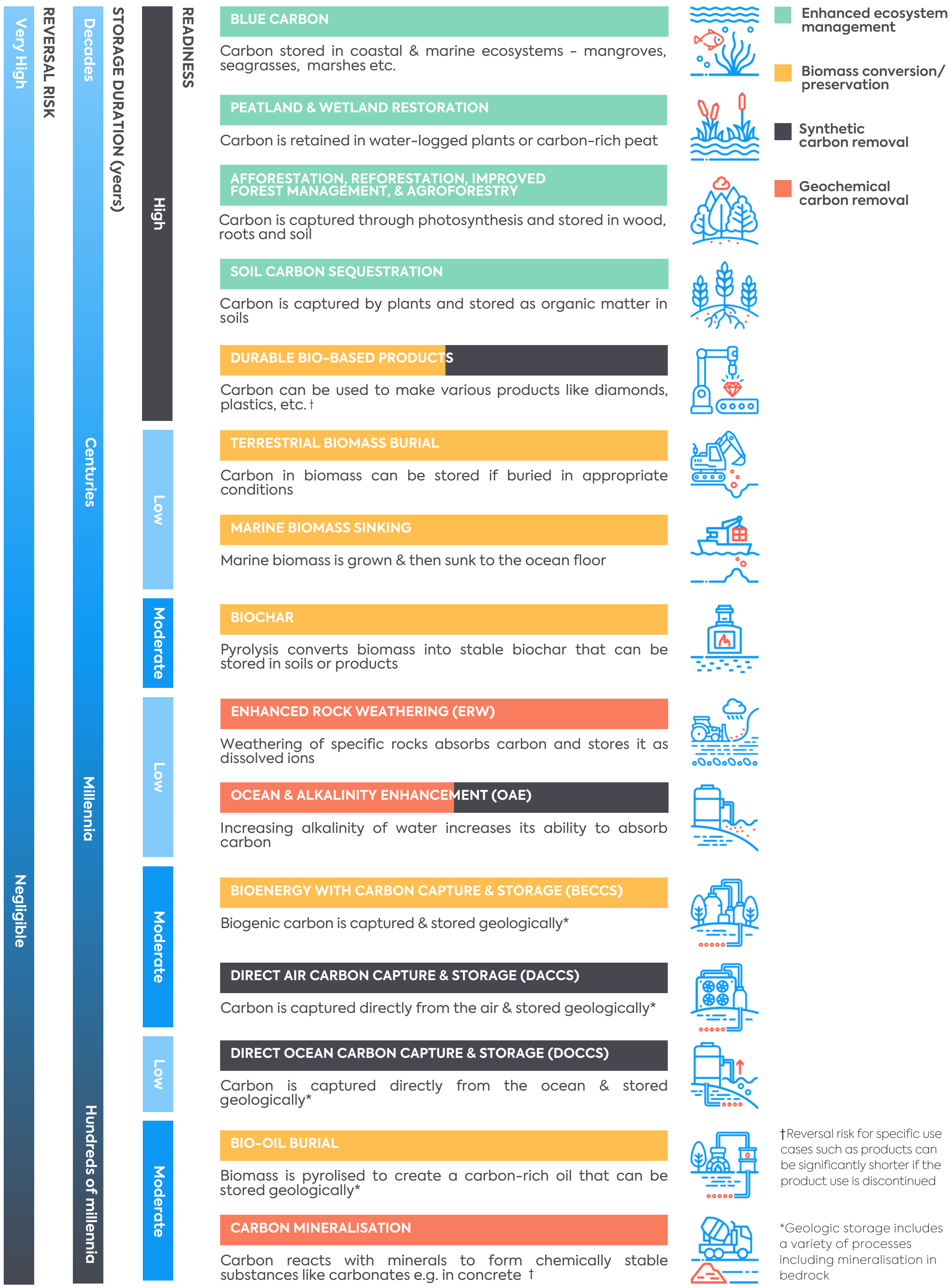


Figure 3. CDR Methods with their respective storage duration and deployment readiness (Carbon Gap).

2.1.1 Enhanced ecosystem management

CDR methods based on enhanced ecosystem management increase the amount of carbon sequestered and retained across both natural and managed ecosystems. By optimising land use or restoring degraded or altered ecosystems, these approaches strengthen the capacity of landscapes to operate as carbon sinks. Methods within this category include:

1. **Afforestation, reforestation and revegetation (ARR)** refers to a set of activities aimed at establishing, restoring or enhancing vegetation cover in a given area: afforestation involves creating forests on land that historically did not have forest cover; reforestation focuses on restoring forests on land that previously supported forest cover but lost it due to natural or human causes; and revegetation is a broader concept that includes the establishment of tree, shrub or herbaceous vegetation to rehabilitate degraded areas, helping to restore ecosystem function and carbon storage.

2. **Improved Forest Management (IFM)** enhances forestry practices to increase carbon sequestration within forest ecosystems, including longer rotation periods, reduced harvesting, and conservation of old-growth stands.

3. **Agroforestry** in Spain is exemplified by the *dehesa*, a land-use system that integrates trees and shrubs into agricultural and livestock systems. This model combines grazing activities with perennial vegetation, enhancing ecosystem resilience, increasing biodiversity, improving productivity, and strengthening carbon storage.

4. **Soil carbon sequestration:**

    a. **Cropland management** encompasses agricultural practices that enhance soil carbon storage and soil health, including direct seeding, zero or conservation tillage to reduce soil disturbance, and the use of permanent or seasonal vegetation cover. These practices increase organic carbon inputs, limit carbon losses, and improve the resilience and productivity of cropland systems.

    b. **Pasture management** refers to livestock management practices, such as rotational grazing, that improve soil health and increase carbon storage by promoting pasture regeneration and enhancing the resilience of grassland ecosystems.

5. **Wetland and peatland restoration** by hydrologically restoring degraded wetland and peatlands, it is possible to restore their natural conditions, which turn them from carbon sources into carbon sinks.

6. **Coastal revegetation** focuses on the restoration and conservation of coastal ecosystems - like mangroves, salt marshes, and seagrasses – that naturally capture and store large amounts of carbon in biomass and sediments.

2.1.2 Biomass conversion/preservation

Biomass-based CDR methods harness the natural ability of plants to absorb atmospheric CO_2 through photosynthesis, storing it in their biomass - leaves, stems, roots, and other organic tissues. To prevent this carbon from returning to the atmosphere via natural decomposition or combustion, these approaches deliberately intervene in the carbon cycle. Biomass is intentionally processed in ways that stabilise or permanently sequester the captured carbon, ensuring long-term storage. Methods included in this category are:

1. **Durable bio-based products** refer to carbon stored in materials such as timber and bioplastics. These products delay carbon release by extending the lifecycle of biomass-derived carbon.

2. **Biochar** is produced via pyrolysis of biomass under low oxygen conditions, resulting in a stale, carbon-rich material. When applied to soils or materials, biochar resists decomposition and stores carbon for decades to millennia.

3. **Bio-Oil Storage** converts biomass into bio-oil via pyrolysis and injects it into stable geological formations. This method sequesters liquid carbon underground for hundreds to thousands of years.

4. **Marine Biomass Sinking** cultivates or collects seaweed and other marine biomass, depositing it in deep ocean layers (>1,000 m). This accelerates the natural carbon pump and sequesters carbon for centuries to millennia.

5. **Terrestrial Biomass Burial** involves harvesting plant biomass and burying it in engineered, low-oxygen environments to prevent decomposition. This method locks carbon absorbed via photosynthesis into stable storage for extended timescales.

6. **Bio Carbon Capture and Storage (BECCS)** combines biomass use with CO_2 capture and geological storage. It prevents CO_2 release from biomass combustion or processing, enabling net-negative emissions.

   a. **BECCS with Combustion** captures CO_2 from biomass combustion in power or industrial plants and stores it underground, while generating usable energy.

   b. **BECCS with Anaerobic Digestion/ Fermentation** captures CO_2 released during biomass breakdown for biogas or ethanol production, diverting it to secure geological storage.

2.1.3 Geochemical carbon removal

Geochemical and ocean-based methods accelerate or enhance naturally occurring chemical interactions between carbon dioxide and reactive rocks or minerals. In nature, such reactions unfold slowly over geological timescales. However, by increasing the surface area of reactive materials—typically through grinding—and applying them to terrestrial or marine environments, the rate of CO_2 conversion and storage can be significantly enhanced. Key methods include:

1. **Enhanced rock weathering (ERW)** applies finely ground rocks or materials rich in alkaline minerals to soils, where they react with ambient CO_2 to form stable carbonates, sequestering carbon over long timescales.

2. **Ocean Alkalinity Enhancement (OAE)** increases seawater alkalinity to accelerate natural CO_2 absorption, converting it into stable bicarbonate and carbonate ions.

   a. **Mineral OAE** involves dissolving alkaline minerals (e.g., olivine, lime) into seawater to boost alkalinity and enhance CO_2 uptake.

   b. **Electrochemical OAE** uses electricity to modify seawater chemistry, increasing its alkalinity, and therefore its capacity to absorb and retain CO_2.

3. **Carbon mineralisation** facilitates the reaction of CO_2 with calcium- or magnesium-rich rocks to form solid carbonates. This can occur in controlled reactors (ex situ) or within geological formations (in situ), enabling permanent carbon storage.

4. **Ocean fertilisation** adds nutrients to ocean regions to stimulate phytoplankton growth and CO_2 uptake. It can be done with iron, nitrogen/ phosphorus or artificial upwelling. Overall, results are variable and may involve ecological risks and rapid carbon re-release.

2.1.4 Synthetic carbon removal

Synthetic carbon removal encompasses engineered systems designed to extract CO_2 from the atmosphere or oceans and store it permanently. Two principal approaches in this category are Direct Air Carbon Capture and Storage (DACCS) and Direct Ocean Carbon Capture and Storage (DOCCS). Both offer the advantage of long-term, measurable carbon sequestration.

1. **Direct Air Carbon Capture and Storage (DACCS)** involves capturing CO_2 directly from ambient air using solid sorbents or liquid solvents. Once captured, the CO_2 is released through the application of heat, pressure, or chemical reactions, yielding a purified CO_2 stream. This concentrated CO_2 is then compressed and stored in geological formations or other long-term sequestration sites.

   a. **Electrochemical DACCS** utilises electrochemical reactions to selectively capture and release CO_2.

   b. **Moisture-Swing DACCS** employs sorbents that adsorb CO_2 in dry conditions and release it when exposed to moisture.

   c. **Mineral Looping DACCS** captures CO_2 by reacting it with Ca- or Mg-rich minerals, forming stable carbonates such as calcite or magnesite.

   d. **Low-Temperature DACCS** (<120 °C) relies on solid sorbents - such as activated carbons, zeolites, silica, or metal–organic frameworks (MOFs) - often functionalized with amines. These materials capture CO_2 through physical or chemical adsorption, with regeneration typically achieved via temperature swing adsorption (TSA) or pressure swing adsorption (PSA), the former being more common due to its lower energy requirements. These systems operate at moderate temperatures (80–120 °C)[8] and may utilise low-grade or waste heat, offering a more energy-efficient approach.

e. **High-Temperature DACCS** (>300 °C) involves liquid-based processes such as calcium or sodium looping, in which CO_2 is absorbed into alkaline solutions (e.g., KOH, NaOH, $Ca(OH)_2$) and later released during high-temperature regeneration (300–900 °C)[8]. While this technique is well established and robust, its high thermal demand significantly increases energy costs, though integration with renewable heat sources may improve its feasibility.

2. **Direct Ocean Carbon Capture and Storage (DOCCS)** targets CO_2 dissolved in seawater, where it exists in large quantities as part of the ocean's inorganic carbon pool. The pH swing method alters chemical equilibria to release CO_2 from solution, allowing it to be captured and stored permanently.

2.2 Selected CDR methods

Theoretically, all CDR methods could be deployed in Spain. Therefore, very few CDR methods were excluded from this study from the start (Figure 4). The most suitable CDR methods for Spain's natural conditions are afforestation/reforestation, soil carbon sequestration, biochar and BECCS.

Bio-oil storage has been dismissed due to economic and scalability constraints. While reversal risks such as migration or GHG release are considered low and manageable through standard drilling and monitoring, the combined costs of production, transport, injection, and technology development remain prohibitive[9]. Mobile pyrolysers capable of processing biomass at scale are still in development, further limiting feasibility. As a result, despite its low risk profile, bio-oil storage is not viewed as a competitive carbon removal option. Furthermore, no studies, initiatives, or projects on biomass injection wells or burial have been identified in Spain, and given the lack of technical references, these approaches were not explored further in this assessment.

Marine biomass sinking was excluded because the specific oceanographic conditions required for long-term carbon storage are not present. Effective biomass sinking depends on very stable, low-oxygen deep waters with minimal vertical mixing, and these conditions are not characteristic of Spain's

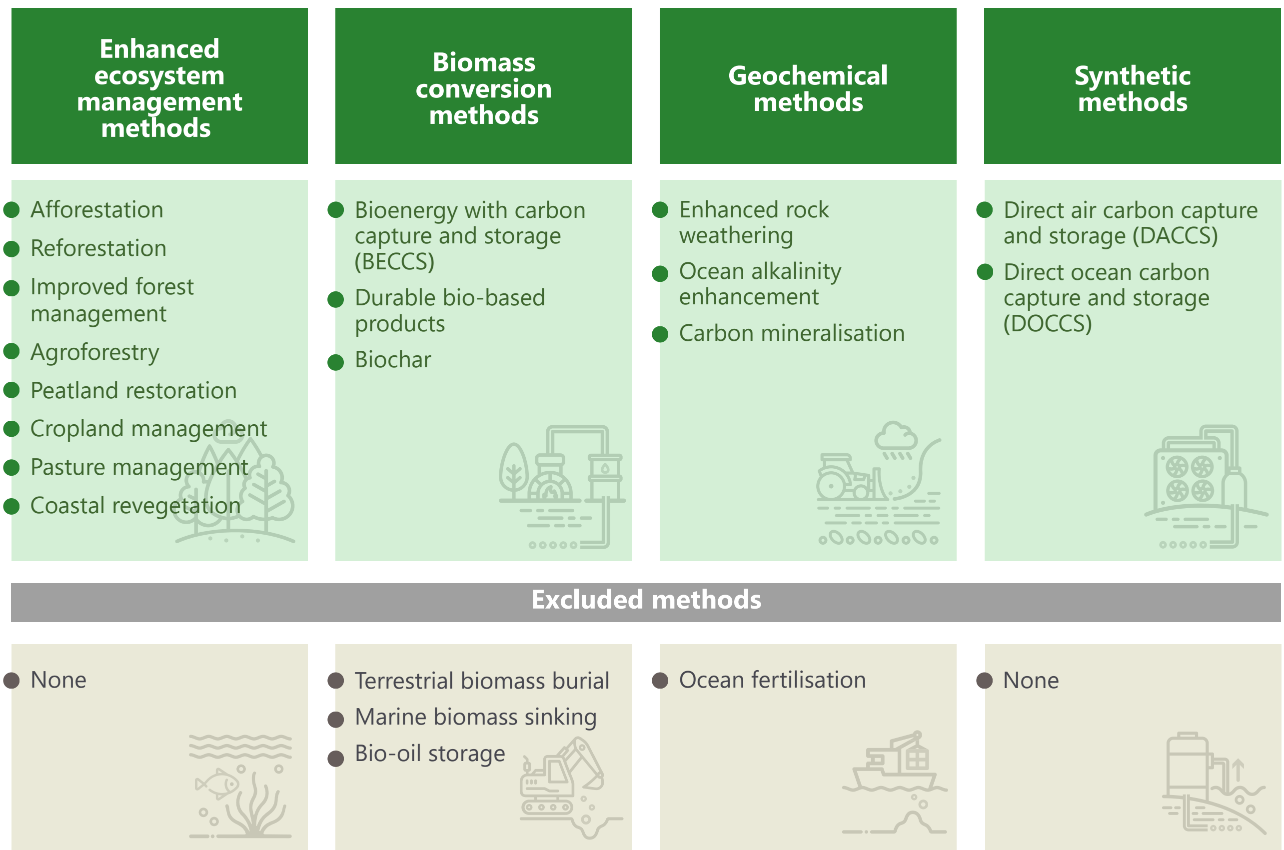


Figure 4. Summary of the CDR Methods included and excluded from the assessment.

surrounding seas. Even if such conditions existed, the environmental risks (such as unknown impact in marine life due to nutrient pollution, altering the natural cycles and balance and oxygen depletion) are a major concern[10,11,12,13].

Ocean fertilisation was considered but ultimately set aside. It is incompatible with Posidonia oceanica restoration, as nutrient enrichment can trigger algal blooms, reduce water clarity, and undermine seagrass recovery. Instead, priority was given to halting the ongoing degradation of seagrass meadows[5,6].

By contrast, DACCS has been included because, despite its current costs, it is a long-term strategic technology in European climate-neutrality scenarios, it does not depend on biomass availability, uses limited land and its costs are expected to decrease as the technology matures.

2.3 Resource requirements for selected CDR methods

To assess the deployment potential of each CDR method, it is essential to understand their resource requirements - such as water usage, land area, and energy consumption - per net tonne of CO_2 removed. However, accurately quantifying these inputs presents two key challenges:

- The diversity of CDR methods, each with multiple variants that differ significantly in design, scale, and operational parameters.
- Limited availability of reliable data, as most methods remain in early stages of development and lack robust field-based evidence.

Moreover, comparing methods requires a consistent basis. Since all CDR approaches generate some GHG emissions during operation, resource requirements must be evaluated per net tonne of CO_2 removed - accounting for emissions subtracted from gross removal volumes. This makes life cycle analysis (LCA) a crucial tool for generating reliable and meaningful data.

The scientific literature offers valuable insights, particularly due to its methodological transparency and rigorous peer review. However, most studies rely on laboratory-scale experiments or modelling, often based on limited datasets. As a result, their applicability to real-world conditions remains uncertain, and few include comprehensive LCAs.

Operational data from companies - those developing pilot projects or commercial-scale deployments - is rare but increasingly available. For instance, application files submitted to the Frontier fund[b] provide performance metrics from actual projects. While these figures reflect current technological capabilities more accurately, they are often self-reported and lack peer review, making them "declarative" in nature.

To overcome these limitations and build a robust database of resource requirements, Carbon Gap partnered with RMI, the Rocky Mountain Institute. The resulting dataset is grounded in three complementary sources: peer-reviewed scientific literature, publicly available Frontier fund applications (across three cohorts), and direct surveys conducted with active CDR operators.

The database will continue to evolve after the publication of this report, but at the time of publication, it includes:

- 442 data points obtained from 129 scientific articles;
- 200 data points obtained from 113 Frontier files;
- 330 data points obtained from 57 survey responses.

The database is accessible on the CRRA website.

The data was compiled to produce consolidated values for each of the resources required for CDR methods. These values are used in the rest of the report to estimate the potential of CDR methods based on the available resource feedstocks. When values are not available from the database or if alternative values are more relevant to the national context, they are explicitly reported, along with their source.

b. Frontier is an advance market commitment backed by major private companies to support the development and early deployment of CDR technologies through advance purchases of CDR credits.

3. Spain's resources and feedstocks

This chapter assesses the availability of the physical resources and feedstocks required to deploy the selected CDR methods. Their current level of availability, and the prospects for the foreseeable future (growth, stagnation, or decline) are determined, and wherever possible, the geographical distribution of each resource is also characterised. The scope of this chapter refers to availability at a national level and future work would be needed to analyse regional and more local contexts.

3.1 Energy

Energy availability in Spain reached **1,864 TWh** in 2023, with electricity generation accounting for **286 TWh**. Projections to 2050 vary widely: in the most conservative case, electricity demand grows by 22%, while in the most ambitious one it increases 2.56-fold and is supplied almost entirely by renewables. Waste heat potential, estimated at **22 TWh** in 2015, is forecast to decline to **10.52–21 TWh** by 2050 due to reduced fossil fuel use and strong industrial electrification. For CDR, the electricity and waste availability in 2050 was estimated at up to **22–31 TWh** and **6–21 TWh**, respectively.

Figure 5 shows the energy flow balance of Spain in 2023[10]. Petroleum products dominate the energy mix (around 50%), followed by natural gas (19%) and renewables (14%), while the use of solid fuels and non-renewable waste is considerably lower. Electricity generation (**286 TWh**) represents about 14% of the available energy, with transmission losses of 22%. Nuclear energy and other renewable energy sources supplied 70% to Spain's electricity in 2023[10,14].

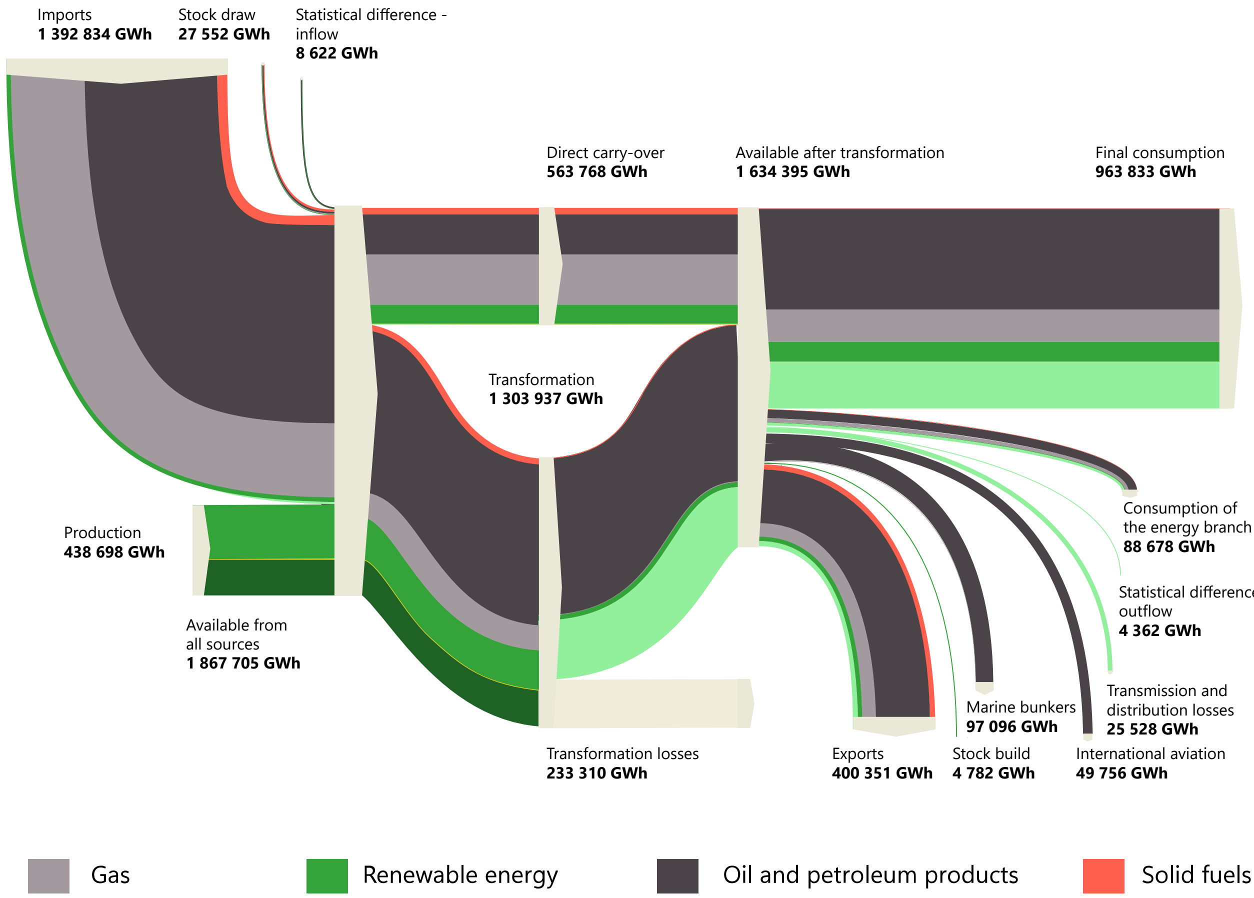


Figure 5. Energy Balance Flowchart in Spain in 2023[10].

3.1.1 Electricity

Electricity is expected to play a crucial role in decarbonising Spain. Renewable electricity generation increased from 33-40% between 2010 and 2019 to 43-51% between 2020 and 2023, revealing the country's commitment to decarbonise its electricity grid. Most of the generated electricity (51-56%) is used by the residential, commerce, and public service sectors (gathered in Figure 6 as "Others"). The industrial sector follows, representing 24-27% of total consumption.

Electricity scenarios

To estimate future electricity availability for CDR, four 2050 scenarios were developed as part of this study (Table1). These scenarios consider two key dimensions: overall electricity generation and consumption (low vs high), and the evolution of the generation mix (stable vs significantly altered by the integration of renewable sources). Regarding the level of generation and consumption:

- Low generation/consumption scenarios assume electricity demand remains largely stable, growing steadily in line with historical trends. This serves as a reference projection, similar to those developed by MITECO[15].
- High generation scenarios incorporate widespread adoption of electric vehicles and growth of the green hydrogen industry, both driving a sharp rise in electricity demand. These projections draw on studies of Spain's electric sector[16].

Regarding the electricity generation mix, two pathways are considered:

- Business-As-Usual (BAU): where current mix remains unchanged
- Dynamic Low-Carbon (DLC): which implies a complete exclusion of nuclear- or fossil-based energy sources.

The electricity generation scenarios for Spain up to 2050 are shown in Figure 7, highlighting different energy pathways: natural gas, other non-renewables, nuclear, and renewables including biofuels.

By 2050:

- Scenario E1 maintains a balanced mix, with renewables and biofuels contributing approximately 35%, natural gas around 30%, and nuclear about 25%.
- Scenario E2 describes a system that becomes almost entirely renewable by 2050, with renewables and biofuels contributing over 90%, and fossil fuels and nuclear nearly phased out.

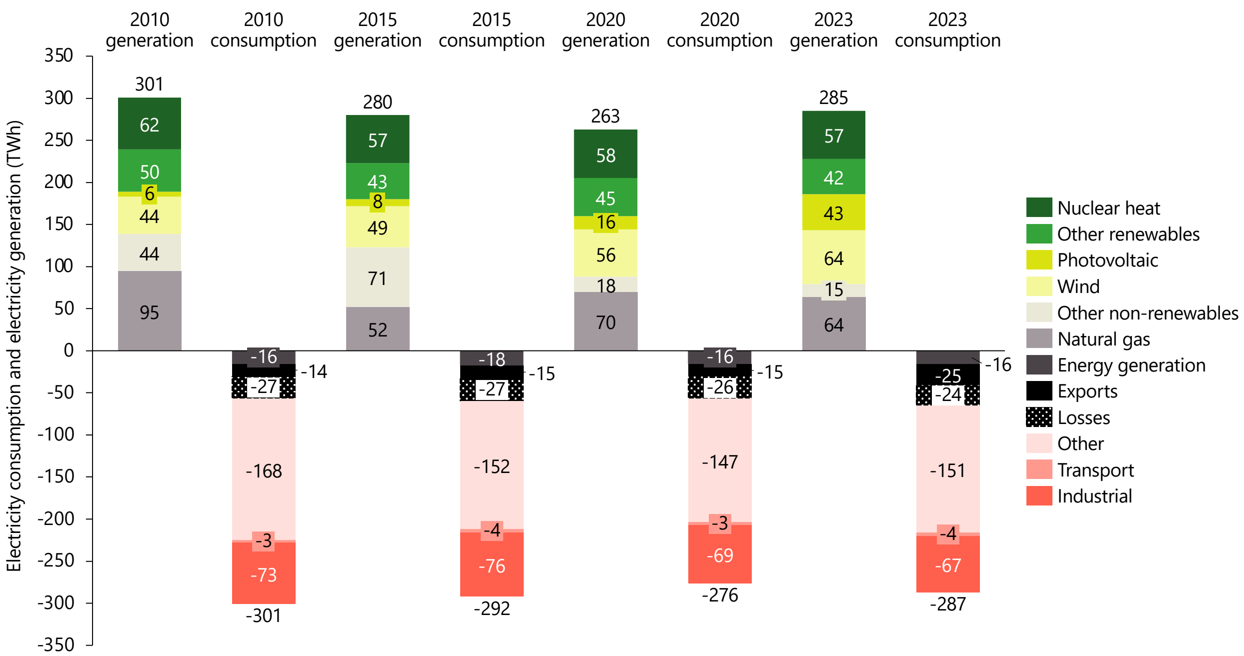


Figure 6. Historical electricity generation and consumption in Spain (2010-2023). "Other" refers to residential, commerce, and public service sectors[10].

Scenario	Expected electricity generation/ demand	Expected electricity generation mix	Description
E1: Stable electricity, stable mix	Low	Business as usual (BAU)	Electricity generation/demand increases by 22% by 2050 according to MITECO projections[15], while the electricity generation mix remains constant.
E2: Stable electricity, renewable mix	Low	Dynamic Low Carbon (DLC)	Electricity generation/demand increases by 22% by 2050 according to MITECO projections[15], and is fully supplied with renewable sources.
E3: High electricity, stable mix	High	BAU	Electricity generation/demand increases by 256% by 2050, according to projections estimated for the Spanish electric sector[16], while the electricity generation mix remains constant.
E4: High electricity, renewable mix	High	DLC	Electricity generation/demand increases by 256% by 2050, according to projections estimated for the Spanish electric sector[16], and is fully supplied with renewable sources.

Table 1. Description of the scenarios for the electricity generation, consumption and generation mix in Spain by 2050.

- Scenario E3 shows a moderate increase in renewable energy, reaching around 45% by 2050, while natural gas and nuclear continue to play significant roles, contributing roughly 30% and 20% respectively.
- Scenario E4 is the most ambitious in terms of renewable deployment, where renewables and biofuels account for more than 95% of electricity generation by 2050, with only marginal use of nuclear and fossil fuels.

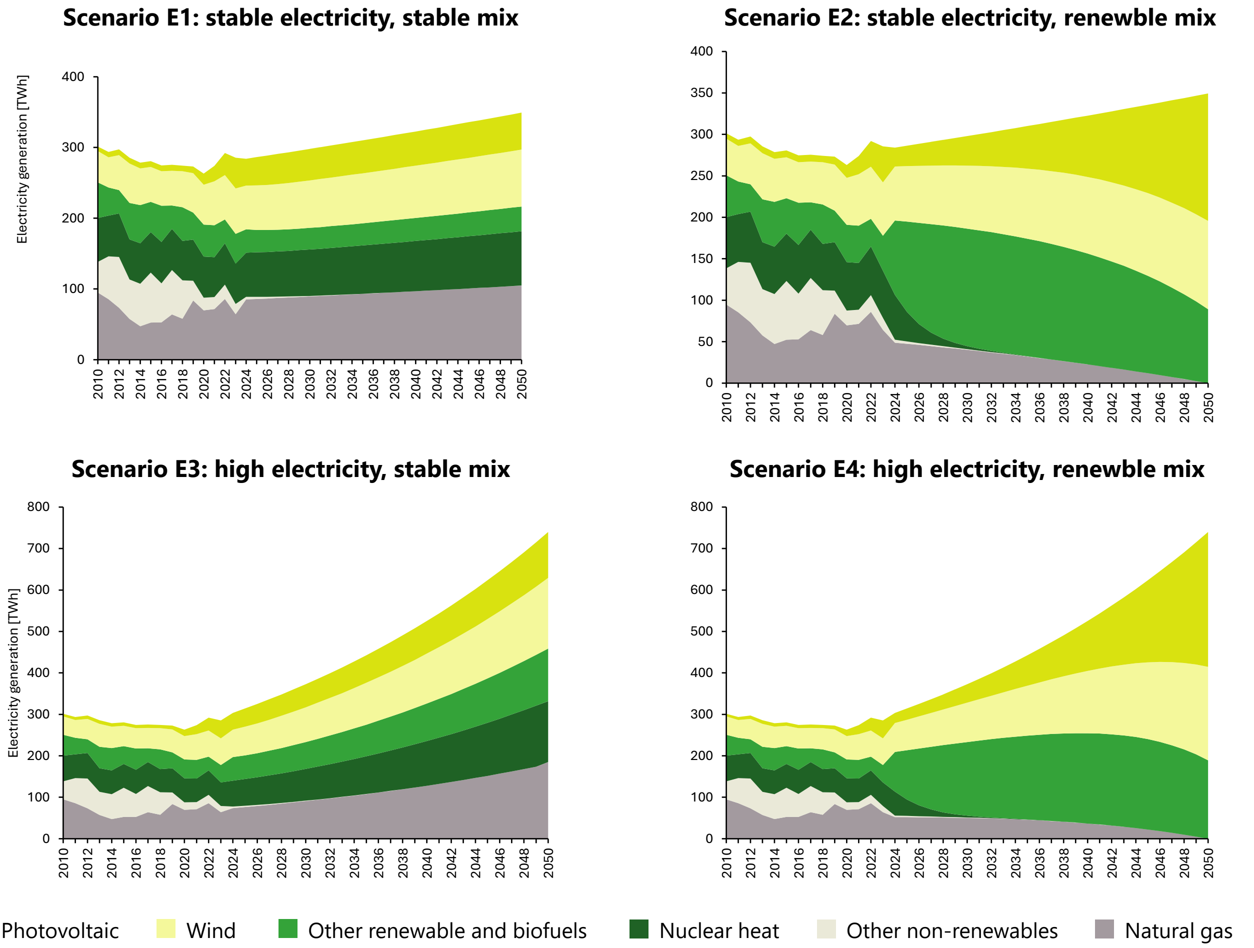


Figure 7. Electricity generation scenarios in Spain by 2050.

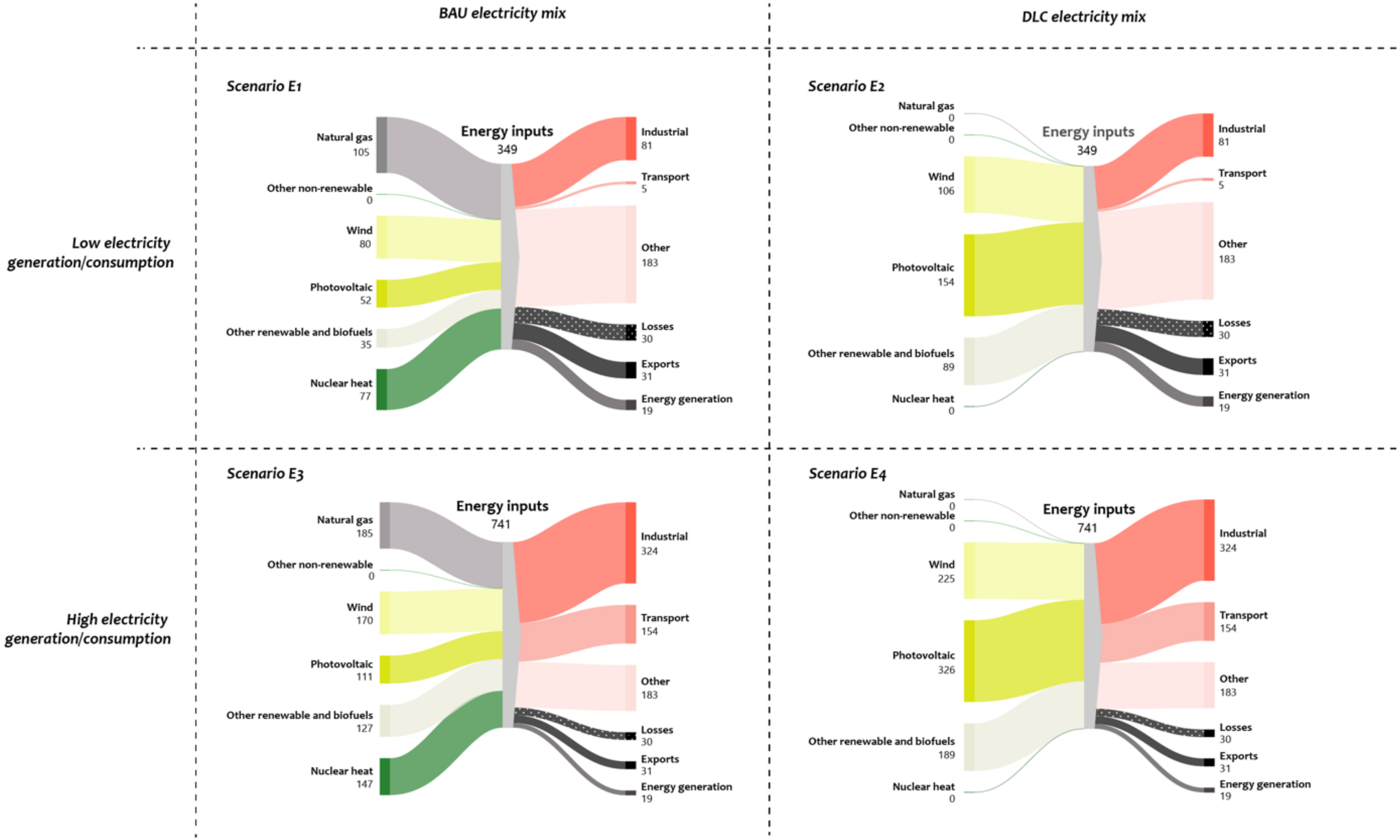


Figure 8. Forecasted electricity balance in Spain by 2050 under the analysed scenarios. Data in TWh. "Other" refers to residential, commerce, and public service sectors.

Overall, the scenarios reflect varying ambition levels of decarbonisation, with Scenarios E2 and E4 aiming for near-total reliance on renewable energy. The electricity balance for Spain in 2050 under the analysed scenarios is shown in Figure 8. The **theoretical maximum availability** of electricity available for CDR is estimated to be **31 TWh by 2050**, based on the assumption that only electricity that is expected to be exported would be available for CDR. The realistic availability is instead described in section 7.3.1.

3.1.2 Thermal energy

Heat is vital for various technological CDR methods, driving the chemical processes for CO_2 capture and regeneration. Different CDR methods have varying heat requirements; for instance, Solid Sorbent Direct Air Carbon Capture (S-DAC) needs low-grade heat, typically between 80°C and 100°C, for sorbent regeneration, while Liquid Solvent Direct Air Capture (L-DAC) demands much higher-grade heat, ranging from 300 °C to 900 °C. A significant source of heat for CDR applications is waste heat, particularly from industrial processes.

Official statistics on thermal energy generation in Spain are unavailable, but a 2015 study[17] estimated waste heat at around **23 TWh**. The largest share (41%) came from waste-off gases at 100–200°C, followed by high-temperature gases (500–1000°C) at 20%. By sector, iron and steel contributed 42% of the total, and the non-metallic mineral industry (cement, glass, ceramics, etc.) contributed 34% (Figure 9). A 2021 study indicates current waste heat potential remains broadly consistent with the 2015 estimates[18].

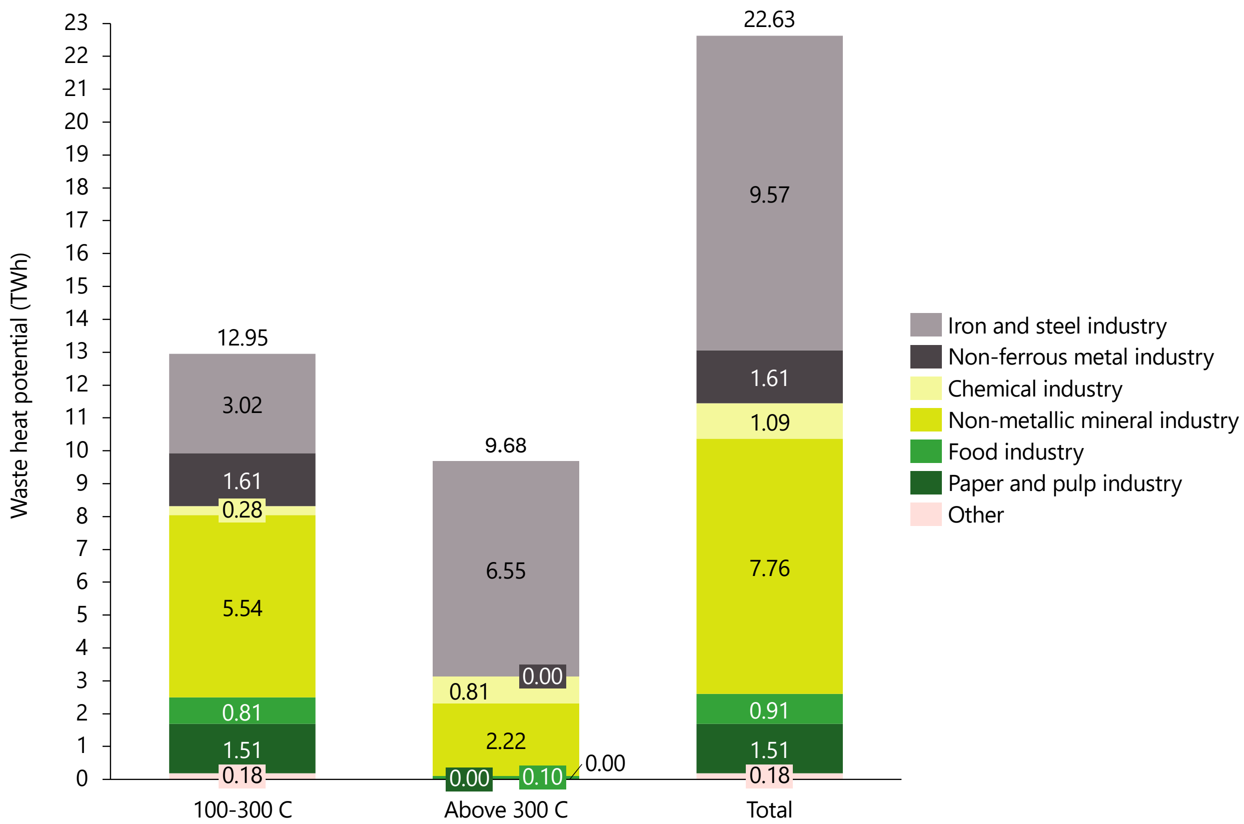


Figure 9. Spain's estimated current waste heat by sector it originated from[17,18].

Scenario	Description
T1: Stable thermal processes	Thermal processes stay at current levels (Figure 10), but new technologies reduce losses by 7%, resulting in less waste heat[19].
T2: Low thermal processes	Thermal processes fall by roughly 50% assuming Spain meets industry decarbonisation targets, driven mainly by electrification[20].

Table 2. Description of the scenarios for thermal processes and associated waste heat in Spain by 2050.

Thermal energy scenarios

No official projections were found for waste heat generation or use in Spain. Therefore, Spain's waste heat potential to 2050 was estimated through two scenarios developed as part of this study and derived from combining alternative thermal energy outlooks, as shown in Table 2.

Figure 10 presents Spain's estimated waste heat potential by 2050. Scenario T1 yields a waste potential of **21.05 TW**h and Scenario T2 **10.52 TWh**, with low-grade heat (~57%) making up the majority, with 12 TWh in Scenario T1 and 6 TWh in Scenario T2.

The **theoretical maximum availability** of waste heat available for CDR by 2050 is expected to be lower than current levels and estimated to be **~21 TWh** (12 TWh for low-grade heat and 9 TWh for high-grade heat, assuming, as per Scenario T1, that thermal demand stays at current levels but new technologies reduce it 7%, resulting in less waste heat.

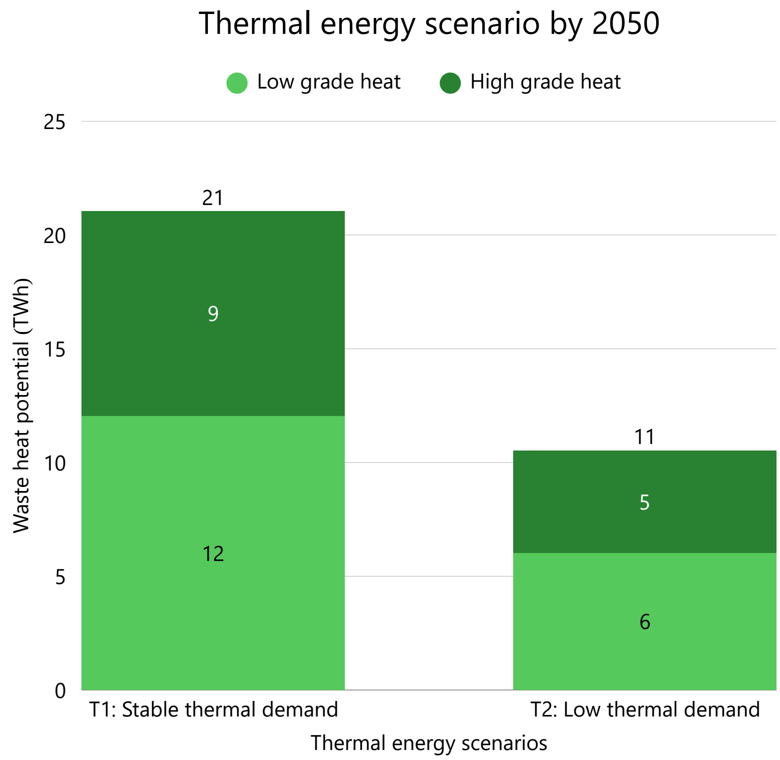


Figure 10. Estimated waste heat potential in Spain by 2050. Low-gradeno the heat refers to temperatures below 300 °C

Resource	Current estimate	2030	2040	2050
Electricity (TWh)	286	298-373	323-525	349-740
Renewable	150	142–317	155 – 300	168–740
Non-renewable	136	56–168	23 – 236	0–332
Maximum theoretical availability for CDR	25	26.6	28.8	**31**
Waste heat (TWh)	22.6	18.9–22.3	14.7 – 21.7	10.5–21.1
Low grade	12.96	10.85–12.78	8.44–12.41	6.03–12.05
High grade	9.67	8.1–9.54	6.3–9.27	4.5–9
Maximum theoretical availability for CDR	22.63	22.31	21.68	**21**

Table 3. Summary of current and forecasted energy availability in Spain according to the electricity and thermal energy scenarios developed. The maximum theoretical energy availability for CDR is also shown.

3.1.3 Conclusions on the energy potential

Spain's current and projected electrical and thermal energy availability, as described in the scenarios above, is summarised in Table 3. Electricity shows a clear shift toward renewables, with surplus generation (exports) assumed usable for CDR, reaching **22–31 TWh**. Thermal energy, by contrast, declines sharply, providing only **6–21 TWh** for CDR by 2050. Overall, renewable electricity is expected to drive the future energy system, while heat remains a secondary but relevant contributor in Spain's future energy mix.

3.2 Water

Spain's distinct climatology, geography, and geomorphology create significant regional disparities in water availability and usage (Figure 11). These factors influence both water resource availability and the degree of exploitation relative to total water available, which ranges from 23% of the total available water in the northern regions to 50% of the total available water in the South and Southwest, where the climate is more arid[10].

Spain has around **100 billion cubic meters (bcm)/year** of water resources, distributed as 73% surface water, 24% groundwater, and 3% other sources (including desalinated water)[16]. Agriculture is the dominant consumer, using ~79% of the total supply, followed by households at 21%. Average domestic consumption is estimated at ~120 L per person per day.

Due to the country's particular climatology, all river basins are regulated with multiple dams and transfers. Spain is the European **leader in wastewater recovery**, with an average recovery rate of 10% in urban areas for grey and black waters. The recovery rate is even higher in water-scarce areas such as Murcia, where water-intensive activities, like agriculture, are frequent. This strong focus on recovery reflects Spain's high-water consumption - the highest in Europe and fifth globally - combined with limited rainfall (except in areas like the Basque Country and Navarra), driving heavy investment in water saving and management.

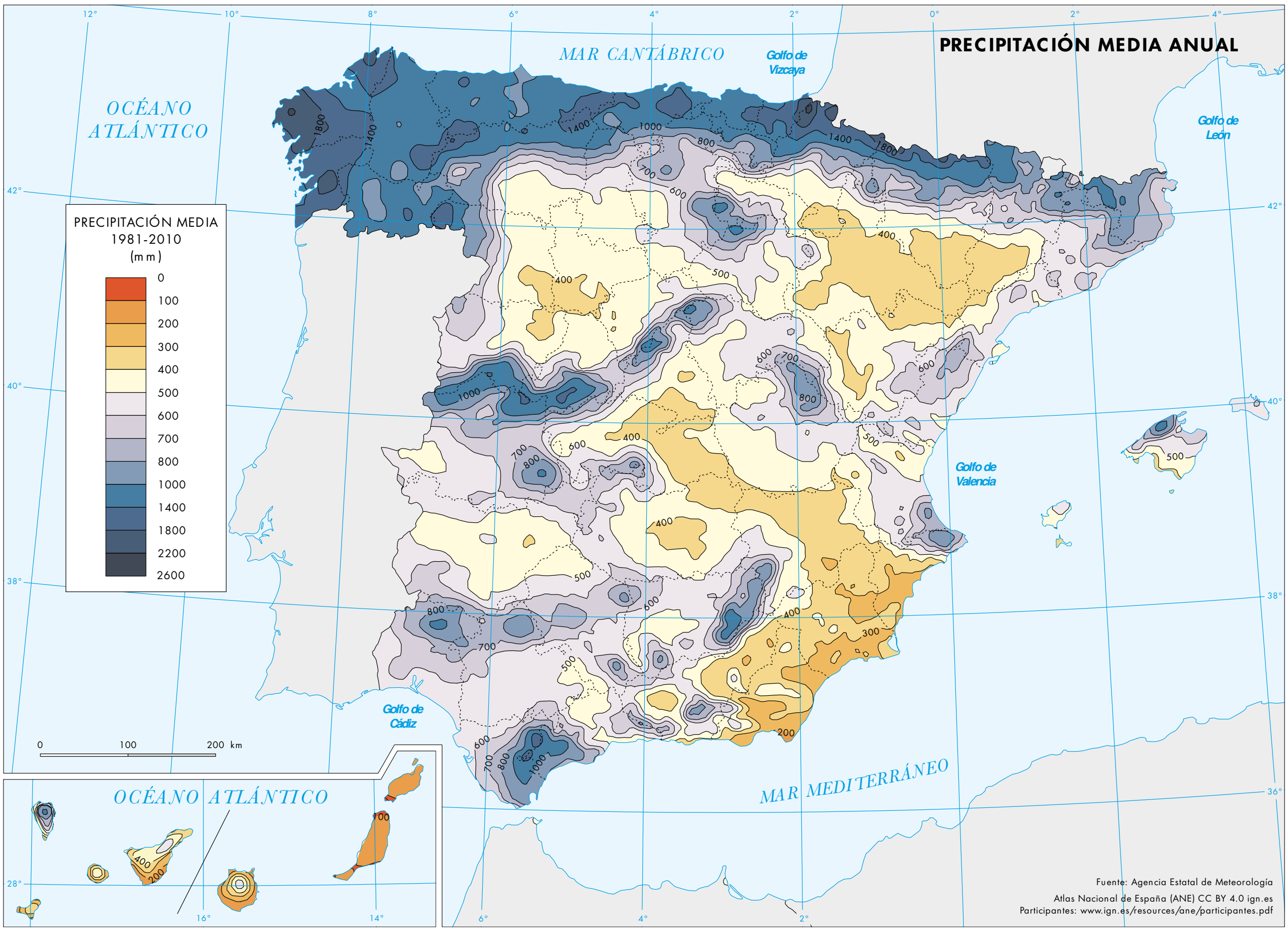


Figure 11. Spanish average rainfall (mm) for the period 1981-2010. Source: AEMET.

Resource	Current estimate	2030	2040	2050
Water (bcm)	111	108.7-111.1	108-111.4	106.2-111.5
Surface water	80.5	79.7-80.5	79.3-80.5	77.9-80.5
Groundwater	29.5	28-29.5	27.7-29.5	27.3-29.5
Other (incl. desalinated)	1	1-1.2	1-1.4	1-1.6

Table 4. Summary of current and forecasted water availability in Spain.

Table 4 summarises the current and projected water availability in Spain under different scenarios. Realistically, a gradual decline in both surface water and groundwater availability is expected, aggravated by increased water demand (both for household and agriculture). To compensate for these reductions, desalinated water is projected to increase, with volumes largely dependent on electricity supply and membrane efficiency.

Spain currently uses approximately 30.38 bcm/year[16], which represent less than a third of the resource (~27.5%). To compensate for the forecasted steady reduction of available water alongside the possible effects of climate change, MITECO has established consumption reduction goals up to 2050, which aim to lower current consumption down to 26.335 bcm, which represents a 15% reduction.

With regards to water resources, the main challenge for CDR is the uneven distribution, potentially prohibiting the deployment of certain methods in the regions where water is already missing. Some CDR methods, like certain DACCS technologies, require ample volumes of water and will need a spatial match between water availability and proximity to CO_2 geologic storage. ERW is also dependent on rainfall for the geochemical reactions to occur on meaningful timescales.

3.3 Land

Land is an essential resource for CDR, as it acts both as a carbon sink and as a foundation for various technological solutions. Each land category offers specific potential: arable land is suitable for biochar, ERW and carbon farming practices; non-arable land

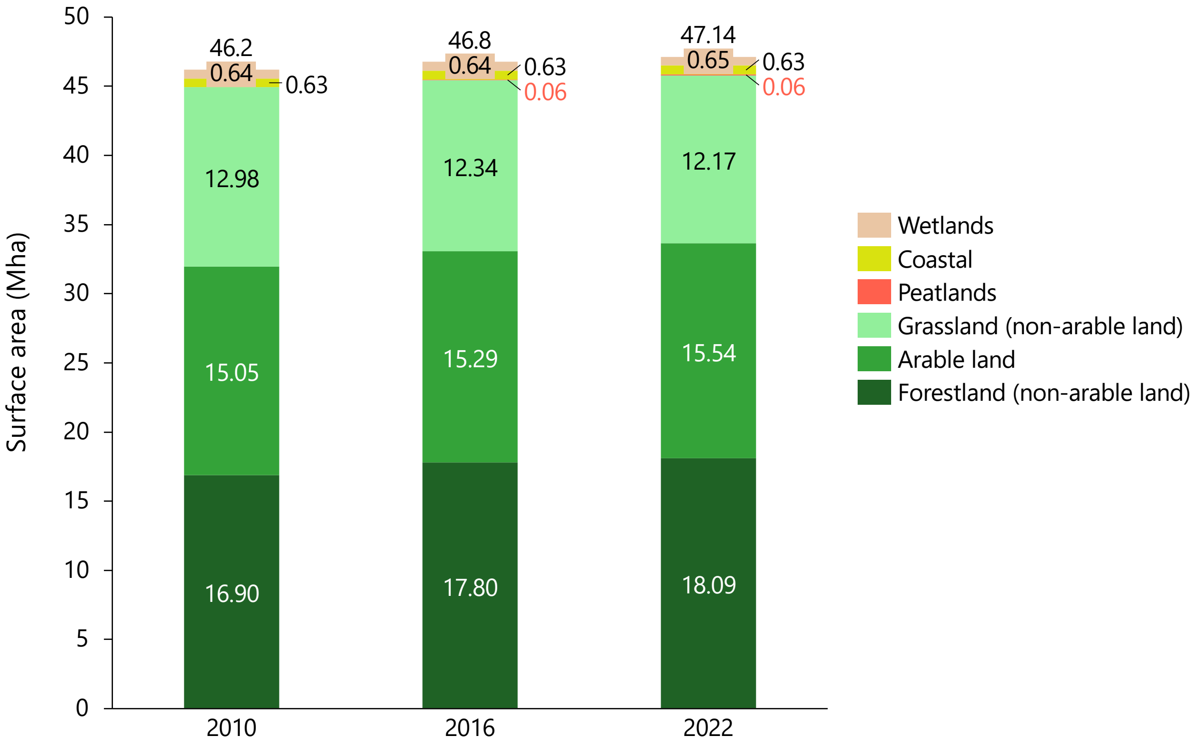


Figure 12. Land use in Spain in 2022 and from 2010 to 2022. Data: Common reporting tables for the National Greenhouse Gas Inventory[22].

for afforestation/reforestation or technological CDR solutions; wetlands for restoration; and coastal zones for restoration of salt marshes or seagrasses. The total surface of Spain is **50.6 Mha**[21] distributed among the land types shown in Figure 12 (except for urban areas and non-rural land).

Since 2010, Spain's forested areas have expanded (2010–2022), driven by rural abandonment and the decline of farming and livestock. By 2050, land use is expected to shift moderately toward a more sustainable balance: agricultural land (especially annual crops) will decline slightly due to rural abandonment, climate change, and reforestation, while permanent and organic crops expand.

3.3.1 Forestland

Spain has extensive forest coverage. In 2022, wooded forestland covered 38.5% of Spain's total surface area, just over **18 Mha**[23]. This extensive coverage presents a significant opportunity for carbon sequestration through enhanced forest management. Notably, as of 2022, ~12.9 Mha (70% of the wooded forestland) is unmanaged, as can be seen in Figure 13, representing untapped potential for climate mitigation.

Forestland includes both wooded (i.e. forests) and non-wooded areas, the latter having a forest character but without a significant tree cover, being dominated by shrubs, natural grasslands, or barren lands. Non-wooded lands cover about 17.9% of the country - over 9 Mha in 2023 - and offer high potential for reforestation[23]. Under a rapid-change scenario, total forest area could surpass **19 Mha** by 2050, with around **8.4 Mha** of non-wooded forest land providing strong CDR opportunities through reforestation, restoration, and improved pasture management. Table 5 shows this scenario adds 1 Mha of new forest (from 18.09 to 19.09 Mha), though only 14.92 Mha would count toward CDR because the rest is already managed. Since Spain's official strategy aims for just a 0.6 Mha increase by 2050, the rapid-change pathway nearly doubles that ambition. The result would be fewer but more sustainable agricultural areas[24], boosting carbon-sequestration and climate resilience.

3.3.2 Cropland

In Spain there is a predominance of traditional Mediterranean crops. Figure 14 shows the distribution of agricultural land by crop type in 2022. Cereal grains stand out (37.5%), followed by olive groves (17%) and vineyards (7.6%). Other crops, such as industrial crops, nuts, forage, and fresh fruit trees, occupy smaller proportions.

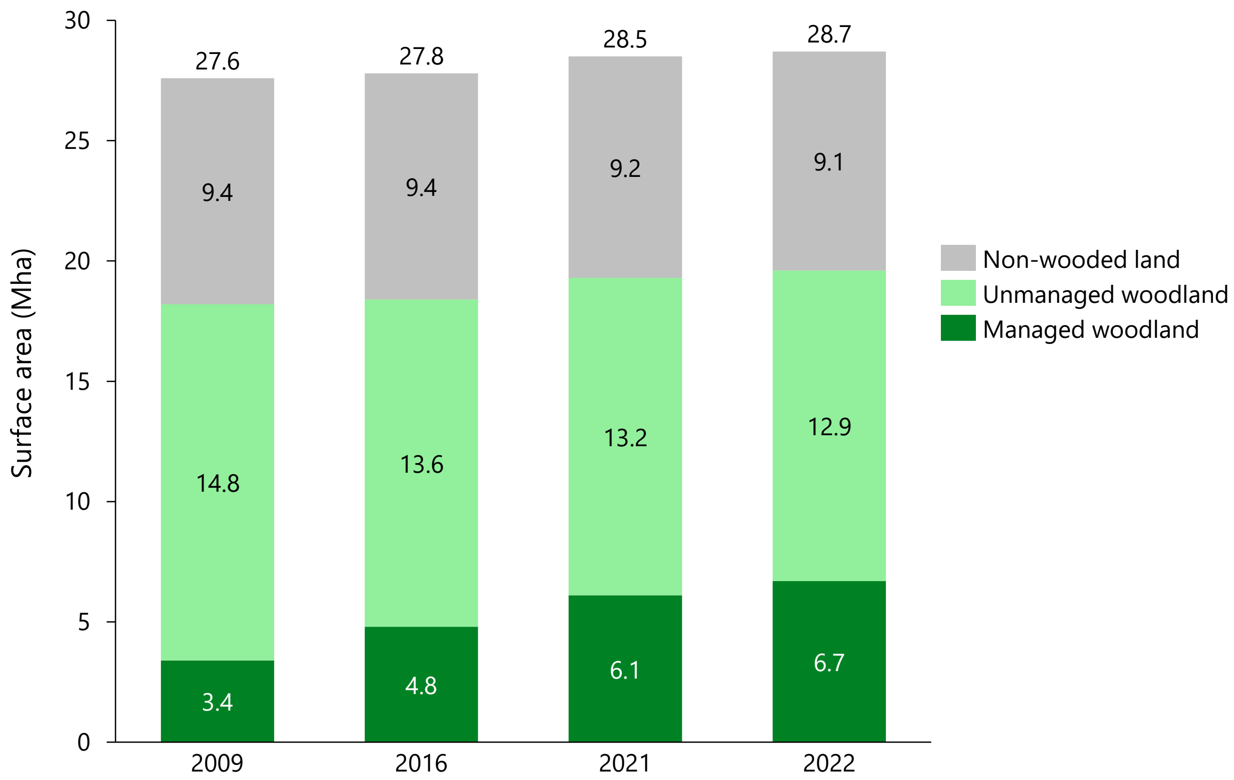


Figure 13. Forestland area in Spain in recent years, data from the Forestry Statistics Yearbook by MITECO[23].

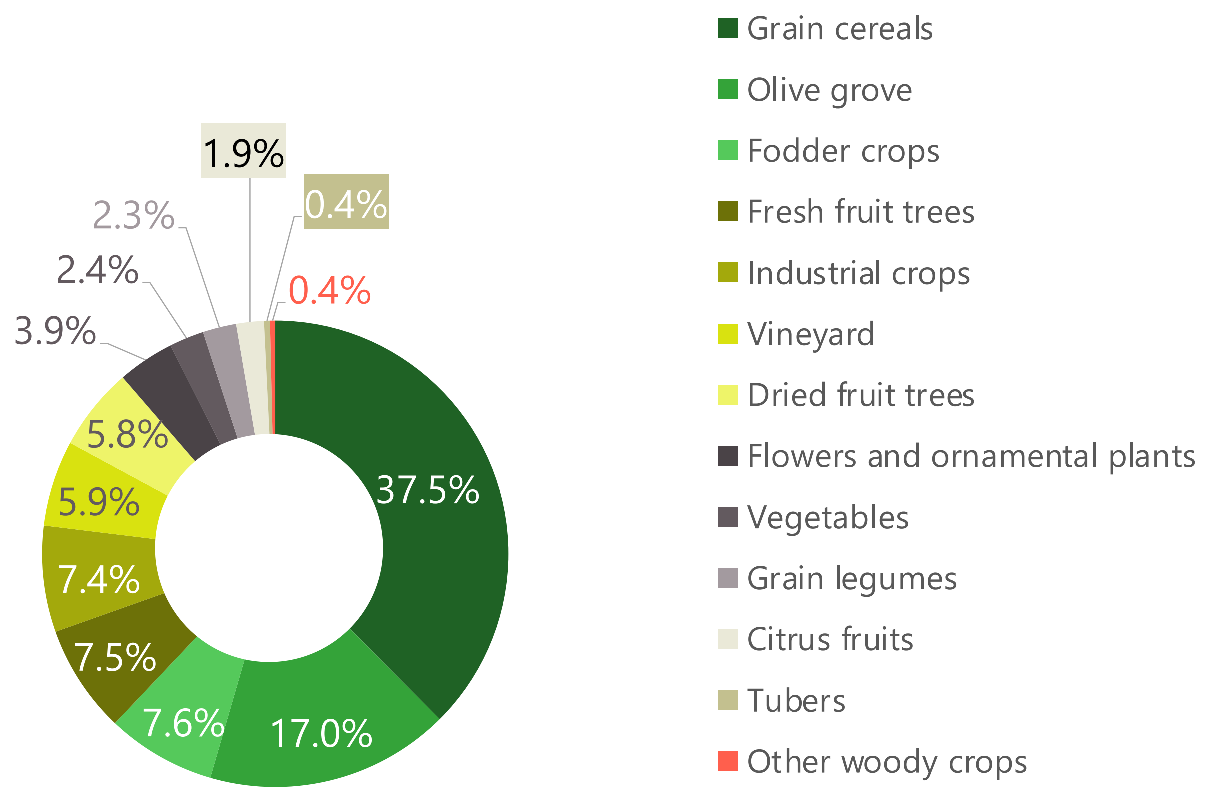


Figure 14. Agricultural area by crop type in 2022, data from Statistics Yearbook by MAPA[25].

Cultivated land, through sustainable soil management and the inclusion of conservation agriculture practices, represents a source of carbon sequestration. In addition, woody crops and even annual crops after harvesting leave a large amount of residue that can be used as biomass feedstocks for other CDR methods, i.e. biochar or BECCS. These lands are also available for ERW activities.

3.3.3 Land scenarios

Over the years, changes in land use have been observed across the Spanish territory that alter the amount of carbon absorbed by natural ecosystems. The following section examines the projected changes for non-aquatic land uses, as aquatic uses are addressed later.

The methodology used to estimate land availability is based on the following references:

- The Spanish Forestry Strategy, horizon 2050[24].
- Trend-based areas derived from MITECO data for each land category.
- The "Corine Land Cover" databases.
- The Ministry of Agriculture, Fisheries and Food (MAPA), through the Crop Area and Yield Surveys (ESYRCE)[26].

In general terms, the approach consists of identifying the most favourable and unfavourable scenarios for forests (tree-covered forest area) and quantifying their surface changes for 2030, 2040, and 2050. Due to these changes in forestland area, estimates are also made for agricultural land and grasslands (including non-wooded forest land) for the same years. The data is presented as a range summarising the results from three land surface change scenarios, with a first value corresponding to a scenario in which the objectives set out in the Spanish forestry strategy are adopted more slowly than expected, the second value corresponding to a more optimistic scenario and, in brackets, the most realistic scenario.

Projection for cropland

By 2050, a moderate reduction in agricultural area in Spain is expected[27], more pronounced in annual crops than in permanent ones, although no drastic loss is foreseen due to population growth and the need to ensure food security. According to projections, **annual cropland** would **decrease** from **9.57 Mha** to **9.46 Mha**, while **permanent cropland** would remain **more stable**, between **5.98 to 5.92 Mha**.

Land	Current estimate	2030	2040	2050	Surface available for CDR in 2050	% of surface available for CDR out of 2050 surface
Annual crops	9.57	9.49 – 9.56 (9.5) ▼	9.32 – 9.59 (9.47) ▼	9.26 – 9.60 (9.46) ▼	**8.27**	87%
Permanent crops	5.98	5.91 – 5.99 (5.97) ▼	5.83 – 6.00 (5.94) ▼	5.76 – 6.01 (5.92) ▼	**3.65**	62%
Forestland	18.09	18.12 – 18.39 (18.2) ▲	18.23 – 18.75 (18.42) ▲	18.39 – 19.09 (18.69) ▲	**14.92**	80%
Grassland and non-wooded land	12.17	12.20 – 11.72 (11.92) ▼	12.28 – 11.41 (11.85) ▼	12.37 – 11.07 (11.77) ▼	**11.77**	100%

Table 5. Summary of current and future land use estimates in Spain in Mha.

Factors such as rural abandonment, lack of generational renewal, water stress, and reforestation and renaturalisation policies explain this trend, which favours forest expansion. Overall, a smaller but more sustainable agricultural landscape is anticipated, with farming oriented towards permanent, organic, and climate-resilient crops.

Spain is currently a leading country in organic farming, and projections indicate that this area will continue to expand through to 2050. According to the Organic Production Statistics from the Ministry of Agriculture, Fisheries and Food (MAPA)[28], organic annual crops could reach 1.3 Mha (compared to the current 0.6 Mha), while permanent organic crops could grow from today's 0.85 Mha to 2.3 Mha by 2050. However, as noted by the 4 per 1000 Initiative: Soil organic carbon as a tool for climate change mitigation and adaptation in Spain, prepared by the Ministry of Agriculture, Fisheries and Food[29], these areas are not compatible with conservation agriculture (which is a CDR practice), so the hectares available for its application will be estimated by subtracting the organic farming area from the total agricultural surface.

Projection for forestland

In the scenario of rapid changes, forest area (including only tree-covered forest land) experiences steady growth driven by reforestation policies and ecological restoration. This growth would exceed the target set by the Spanish Forestry Strategy horizon 2050[24] to reforest 0.6 Mha between now and 2050. It would rise from the current **18.1 Mha** to **19.1 Mha** in 2050, reflecting the progressive growth of managed forests and the gradual conversion of grasslands and marginal agricultural land into wooded areas.

In the conservative scenario, forest expansion is limited, reaching only **18.4 Mha** in 2050 assuming lower reforestation effectiveness and greater impact from wildfires or droughts.

In Spain, there are two forest management certification mechanisms, FSC and PEFC. The forest area available for the application of IFM would be the expected forest area minus the forest area expected to be certified by FSC and PEFC by 2050 according to a trend scenario. In addition, Spain has 2.42 million hectares of forest land designated for dehesa; this area is used for agroforestry, so IFM cannot be implemented there.

Projection for grassland

Grasslands and non-wooded forest land show a slight downward trend, declining from the current **12.2 Mha** to **11.1 Mha** by 2050, depending on the scenario.

The scenario of rapid changes foresees a significant contraction (−9%), associated with the abandonment of extensive livestock farming, reforestation of non-wooded forest areas, and the natural rewilding of these lands; the conservative scenario maintains values close to current ones due to the failure of reforestation efforts, wildfires, and the effects of climate change.

Non-wooded forest land is considered potentially suitable for the implementation of CDR measures through reforestation and ecological restoration projects. Under a "Business as Usual" (BAU) projection developed based on historical data, Spain is expected to have around **8.4 Mha** of non-wooded forestland by 2050. This land represents non agricultural areas without a defined use and is

Box 1. The dehesa system

Agroforestry in Spain is centred on the *dehesa*, a semi-natural Mediterranean ecosystem with an open tree layer (mainly holm and cork oaks) combined with herbaceous pastures for extensive grazing. Formed through the historical transformation of Mediterranean forests, the *dehesa* integrates agriculture, livestock, forest uses (acorns, firewood, cork), and diverse ecological functions. Its scattered trees and low canopy cover foster biodiversity, multifunctional land use, and resilience to disturbance, making it one of the Iberian Peninsula's most valuable cultural landscapes.

Dehesas typically show a canopy cover fraction (FCC) of 5–65%. Areas with 5–20% FCC are classified as pasture, while those with 20–60% are forestland. A seminar by the Spanish Society of Forest Sciences, UVa INIA, CSIC, and the Extremadura Government[30] reported that 31% of Spain's *dehesa* area falls within the 5-20% FCC range. About **1.09 Mha** of *dehesa* currently has an inadequate canopy cover fraction[30], due to factors such as overgrazing, lack of planning in silvopastoral management, excessive firewood extraction, high game pressure, forest fires and, in recent years, the increasing incidence of root rot and other processes that cause decline, commonly grouped under the term "*La Seca*", making them prime candidates for CDR methods.

the only space where new managed pastures could realistically be established, since existing grasslands are already considered managed and needed to meet future food demand without major dietary shifts. Only part of the 8.4 Mha can be used for pasture, as the area must also accommodate reforestation and agroforestry. The remaining grassland is directed to pasture management, ensuring the whole area contributes to CDR through a balanced mix of reforestation, agroforestry, and improved pasture practices.

3.3.4 Wetlands and Peatlands

Wetlands, including bogs, lagoons, saline basins, peatlands, and marshes (IEZH, 2030), are key aquatic ecosystems. When degraded, they emit GHGs, worsening climate change; restoring them is therefore a powerful mitigation tool. Spain hosts **647 kha of wetlands**, of which ~73% (**488.51 kha**) are in medium or poor condition (RAMSAR, MITECO). **Peatlands** are scarce and fragmented, covering only **60 kha** (<0.04% of the territory)[16]. According to the latest report on the EU Habitats Directive (2013–2018), none are in favourable condition: 88% are rated as inadequate or bad, and the remaining 12% are of unknown status (MITECO, 2018), showing clear deterioration compared to 2007–2012, when no peatland was rated bad or unknown and one was considered favourable.

Hydrological restoration, supported by paludiculture and monitoring, is key to recovering peatlands as carbon sinks. National experience is limited, but successful projects have applied Northern European techniques, mainly ditch blocking and *Sphagnum* revegetation. Although results span less than five years, they appear highly effective. Among restoration initiatives, the LIFE Tremedal project in northern Spain is the largest (170 ha), restoring peatlands and mountain wetlands through drainage blocking and reforestation. By raising the water table and re-establishing wetland vegetation, it achieves about 2.9 t CO_2/ha per year of net carbon burial. Two smaller projects - the Padul Wetland Pilot (18 ha, Granada) and Tremedales de Orihuela (6 ha, Albarracín) - also converted carbon sources into sinks using similar methods.

Under a Business-as-Usual (BAU) path, Spain's only benchmark is its modest wetland restoration rate, with no evidence that current efforts could scale to close the 2030 sink gap. Achieving system-level impact would require a dedicated peatland program with clear targets, secured financing, and standardised MRV aligned with PNIEC and EU rules. Priority actions include mapping and ranking peatlands, scaling proven restoration techniques, and ensuring long-term monitoring.

Peatlands, however, remain a low priority in the Long-Term Climate Strategy (ELP 2050). Expansion is unlikely, degradation may worsen under land-use and climate pressures, and initiatives are limited - making large-scale impact improbable. Even full restoration of the **60 kha** of degraded peatlands would yield only **~0.16 MtCO_2 annually**, which is an unrealistic outcome even in a very ambitious scenario. Based on data from LIFE Tremedal, Padul

Peatland scenarios	Restoration per year in 2050 (kha)	Carbon Captured (ktCO_2/year)
P1: Baseline	**0.18**	**0.51**
P2: Conservative	0.73	1.97
P3: Reference	0.90	2.46
P4: Ambitious	0.97	2.61

Table 6. Possible scenarios assessed for peatland restoration by 2050. P4: Ambitious is the one assumed in the theoretical scenario described in Chapter 4.

Wetland Pilot, and Tremedales de Orihuela, a weighted average burial factor of 2.7 tCO_2/ha per year is a reasonable estimate of Spain's peatland CDR potential.

With no progress to date, the baseline scenario presented in Table 6 is most realistic. Still, for comparison, more optimistic 2050 pathways have been modelled: the ambitious case achieves over 500% above baseline, while the conservative scenario delivers roughly four times current capture.

3.4 Coastal marine areas

Spain has 5,755 km of coastline, 172,888 km2 of territorial waters and a saltwater processing capacity of more than 1.97 bcm/year, of which 26% (1,404,000 m3/d) corresponds to brackish water. Spain has restricted sovereignty over 104 Mha of marine space. Marine space is fundamental to ascertain whether the country can implement marine CDR methods such as coastal revegetation, OAE, and direct ocean capture.

3.4.1 Coastal infrastructure relevant to CDR

Spain has significant **desalination capacity**, exceeding 5,400,000 m^3/day (**1.97 bcm/year**) to meet its intensive water demand, especially from coastal regions. Desalination plants can support CDR by using their brine waste to capture and store CO_2 through mineralisation. Emerging methods also use electrochemical processes to convert brine into compounds that absorb CO_2. Integrating CDR into desalination leverages existing infrastructure, offering a dual benefit for water and climate goals.

Desalination plants, particularly those located in water-scarce regions in the Mediterranean basin, present a unique opportunity to support CDR through ocean-based mechanisms. These facilities produce large volumes of **brine waste rich in alkaline minerals** such as magnesium and calcium, which are key inputs for OAE.

The Carboneras desalination facility in southeastern Spain is one of the largest in the region, supplying freshwater primarily for agricultural usage, according to its technical specification plans, 1 m^3 of desalinated water at this plant results in approximately 0.43 kg CO_2e emissions, largely due to energy consumption. However, by recovering and repurposing the brine byproduct, desalination plants like Carboneras could be retrofitted to serve not only for freshwater production to supply regional demand, but also as a source of mineral feedstock for CDR.

The current desalination capacity in Spain is distributed as follows:

- Large plants, able to treat more than 10,000 m^3/day, represent **77%** of the capacity with 1.52 bcm/year
- Medium plants, with capacities of 500–10,000 m^3/day, represent **22%** of the capacity, with 0.43 bcm/year
- Smaller plants only represent **1%** of the installed capacity with 0.02 bcm/year.

Rainfall in coastal areas in Spain is highly irregular, with year-to-year variations of up to 30%. Water consumption from households, services, industries, tourism, and municipal consumption accounts for only 15–20% of the total volume, whereas agricultural water use can be up to six times higher.

The map below (Figure 15) provides an assessment of regions suitable for carbon-sequestration measures. The map highlights large desalination plants - whose brine discharges and nearby tide-blocking infrastructures (e.g., ports) hinder *Posidonia* survival - alongside highly populated coastal areas that add nutrients and potential leachates to the marine environment, as well as designated marine reserves that could be suitable for *Posidonia* restoration.

3.4.2 Marine zones for seagrass restoration

Due to overexploitation of marine resources, Spain has established 12 Marine Reserves to support sustainable fishing and specific protection measures to achieve the recovery of species of

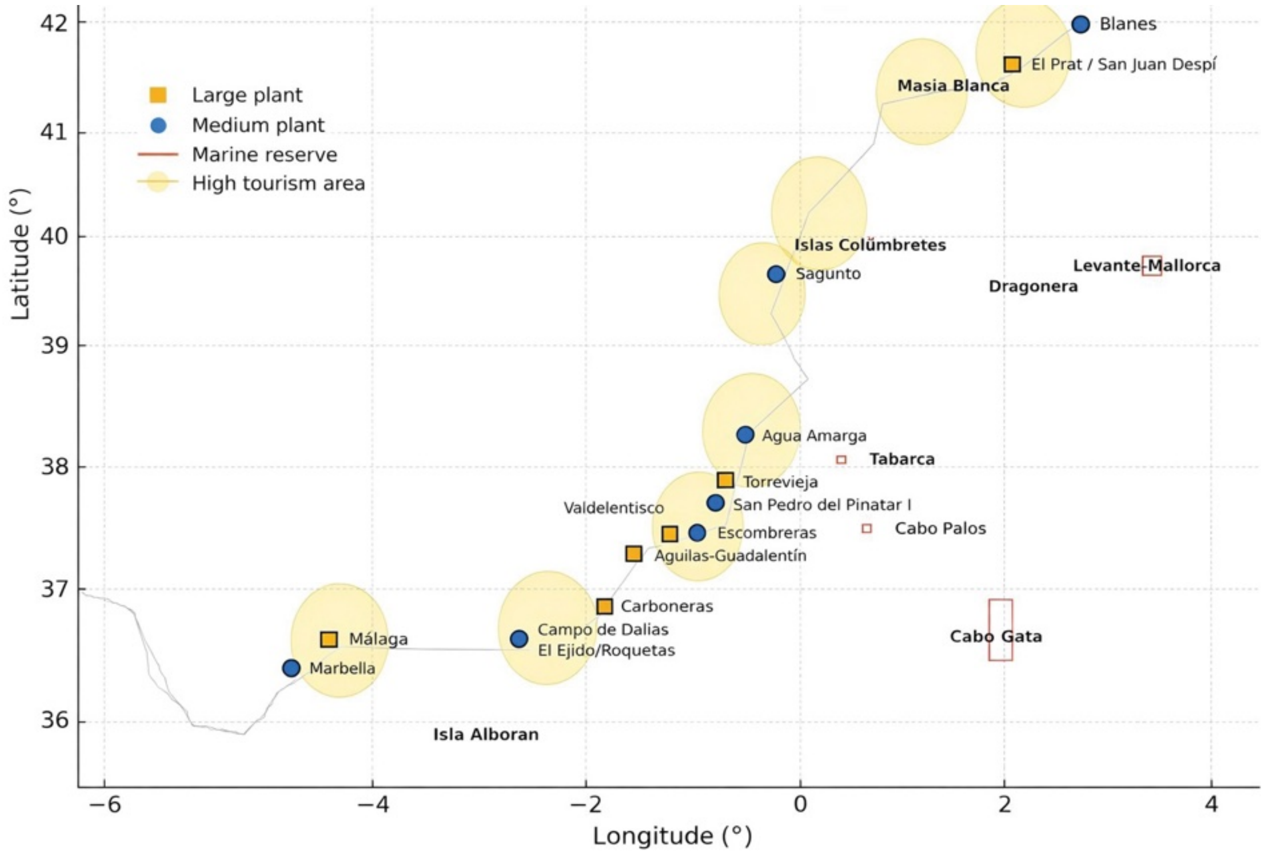


Figure 15. Compound map of high tourism areas, desalination plants and marine reserves in Spanish's Mediterranean Sea.

interest. The 9 Mediterranean marine reserves host dense *Cymodocea nodosa* and *Posidonia oceanica* meadows, given *Posidonia oceanica*'s carbon burial productivity, restoring these meadows offers strong biodiversity, environmental and economic benefits.

Posidonia should be excluded from anchoring hotspots, desalination outfalls, and highly touristic zones, where growth conditions are unreliable. Well-enforced protected areas offer the best feasibility. Site selection should remove brine footprints and anchoring pressure, then prioritise areas by light, turbidity, wave exposure, and protection level. With proper controls, *Posidonia* restoration can coexist with coastal economies.

Given these constraints and considering that the baseline is 0 kha, a realistic restoration surface is **9.91 kha**, with a theoretical maximum of **13.19 kha** from the 49.6 kha that have been lost over the past 50 years[31].

Assessing carbon-capture potential and identifying suitable restoration areas requires understanding marine zoning, since permitted uses determine which techniques can be applied. Long-term CO_2 sequestration must be evaluated through carbon burial rather than net fixation, which only reflects short-term biomass growth.

Using a conservative estimate, a healthy *Posidonia* meadow contains about 450 shoots/m² (50th–60th percentile), equivalent to roughly 2.43 tCO_2/ha/year. Restoration projects in Spain show a survival rate of Posidonia over 91% after four years, demonstrating that degraded meadows can be effectively restored.

Given the ecological importance and carbon-sequestration capacity of seagrass ecosystems, preserving existing Posidonia meadows and partially recovering degraded areas should be prioritized over less mature or uncertain alternatives.

These estimates do not account for additional ecosystem services provided by Posidonia meadows, such as mitigating ocean acidification. Lower seawater pH increases atmospheric CO_2 uptake because the gas is more soluble in water than in air; oceans are estimated to absorb 30–40% of atmospheric CO_2, converting it into carbonic acid and further lowering pH[11].

3.5 Natural conditions

Spain's varied geography and climatic zones - from the humid Atlantic north to the arid Mediterranean southeast – shape CDR feasibility and durability. As shown in Figure E.1 in Annex E, four major climate zones dominate:

- **Hot summer Mediterranean** (Csa): Hot, dry summers and mild to cold, wet winters. Widespread across the Iberian Peninsula, excluding the north, mountain ranges, parts of Murcia and South Valencia, and the Canary Islands. Madrid is a typical example of this climate zone.
- **Cool summer Mediterranean** (Csb): Similar to Csa but cooler, with no month averaging above 22 °C and higher rainfall. Found in elevated areas and parts of Galicia; Salamanca is representative.
- **Semi-arid steppe** (BSh/BSk): Concentrated in southeastern Spain, including Murcia, south of Valencia, Lanzarote, and Fuerteventura. Characterised by extreme summer droughts and heat, mild/warm winters, and sparse rainfall mainly in spring and autumn.
- **Oceanic** (Cfb): Limited to the north (northeast of Galicia, Basque Country, Asturias, Cantabria, and Navarre). Marked by frequent rain, occasional snow, and mild/cool temperatures without extreme heat or cold.

Land-based CDR (forests, soils, wetlands/peatlands) is most reliable in cooler, wetter Csb/Cfb zones, where biomass growth and soil moisture support higher sequestration and lower reversal risk. In Csa and BSh/BSk, summer drought, heatwaves, and wildfire elevate reversal risks and water demands; here, projects should favour drought-adapted native systems, water-efficient agro practices, fuel load management, and conservative permanence assumptions.

Geochemical CDR (ERW, carbon mineralisation) depends on warmth as well as moisture. Year-round temperate Cfb and spring and autumn in Csb offer the most consistent kinetics. Csa can deliver strong winter–spring pulses but faces summer moisture limits and erosion/dust control challenges. Implementation of CDR methods in BSh/BSk require access to additional moisture (e.g., irrigated or organic-amended soils) and careful management of particle handling and trace metals to prevent pollutant dusts and runoff because, due to scarce precipitation, particles have a longer life period and tend to accumulate.

Synthetic CDR (such as DACCS/BECCS) benefits from abundant solar and growing wind power plants, but the site location must balance water availability and cooling loads more challenging in Csa/BSh against the milder conditions of Cfb/Csb.

Across all methods, co-location with low-carbon power and (where relevant) CO_2 transport–storage options is essential. Overall, Spain calls for a portfolio strategy: scale land-based and ERW in Cfb/Csb; deploy engineered options where water/power constraints are solved in Csa/BSh; and pair every project with climate-specific MRV and fire/drought contingency plans.

3.6 Biomass feedstocks

The total biomass produced in Spain is ~174 Mt considering the total pool of material generated annually in forests and agriculture, together with biogenic waste streams such as livestock manure and slurry, sewage sludge, municipal solid waste, industrial residues, urban green waste, and paper and cardboard.

From that, Spain currently (2025) only consumes **~16 Mt** of biomass and biogenic waste for energy purposes per year[32]. Of the total, about 9.1 Mt correspond to forestry biomass, 4.2 Mt to agricultural and agro-industrial biomass, and 2.9 Mt to biogenic waste, which includes livestock manure, sewage sludge, municipal solid waste (MSW), and other industrial biogenic residues (see Annex C.1). Mainly using forestry residues and agricultural residues for combustion, energy crops for both fermentation and combustion, and manure and slurry for biogas production through anaerobic digestion.

Given that current consumption is well below the available potential, and that biomass availability is expected to vary only minimally in the future, the CDR potential values are taken as a reference for the 2030 projection (Figure 16).

The map in Figure 17 illustrates the spatial distribution of bioenergy-related facilities across Spain, including biomass combustion plants, biogas units, and cogeneration systems using renewable or waste-derived fuels. The high density of installations - particularly in industrial regions such as Catalonia, the Basque Country, Andalusia, and Castilla y León - reflects the existing infrastructure that could serve as a foundation for future BECCS deployment. This network highlights significant opportunities for integrating carbon capture methods in both power and heat generation from biogenic sources.

Anaerobic digestion plants for biogas and biomethane play an important role in Spain,

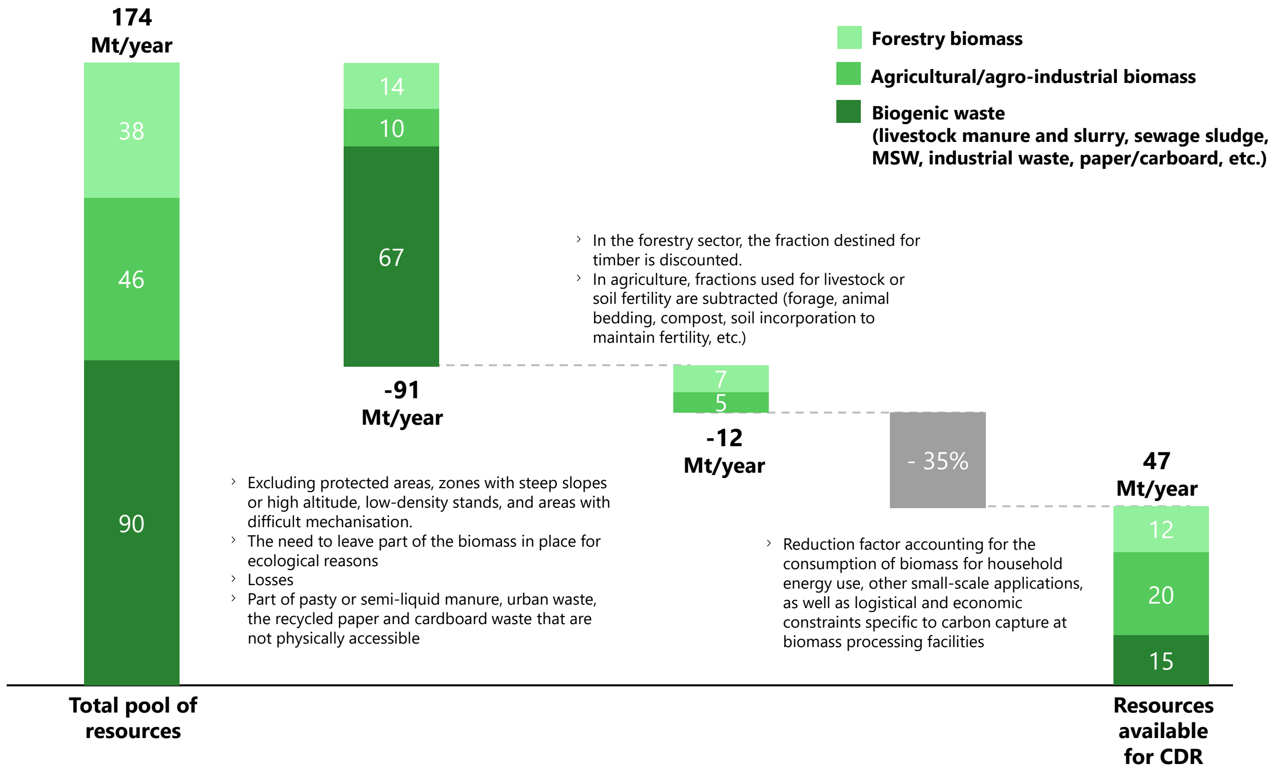


Figure 16. Estimated available biomass for CDR, 2030, in Mt/year (DM or RM).

supported by abundant livestock manure and slurry. Biomass combustion facilities complement them by processing low-moisture or otherwise unsuitable streams, such as woody and lignocellulosic residues. Industrial cogeneration makes smaller contributions but highlights the use of agro-industrial by-products, while the bioethanol sector adds further diversity, drawing on widely cultivated crops as a stable feedstock for first-generation biofuels[38]. Thermochemical processes such as pyrolysis and gasification, though still limited to pilot projects, offer complementary pathways for heterogeneous

Box 2. Methodology to estimate biomass available for CDR

To estimate biomass feedstocks, the analysis began by considering the total pool of material generated annually in forests and agriculture, together with biogenic waste streams such as livestock manure and slurry, sewage sludge, municipal solid waste, industrial residues, urban green waste, and paper and cardboard. From this broad pool, the accessible potential was then defined by applying technical and ecological constraints: biomass in protected areas, steep slopes, high altitudes, or low density stands was excluded. Losses and the need to leave part of the material in place for ecological reasons were also considered. Fractions of manure, urban waste, and recycled paper or cardboard that were not physically recoverable were discounted.

The next step was to determine the available potential, subtracting biomass already committed to other uses. In forestry, this meant discounting the share destined for timber, while in agriculture, portions used for forage, animal bedding, compost, or soil incorporation to maintain fertility were removed. Finally, from this available pool, a further reduction was applied to estimate the fraction realistically accessible for CDR. This adjustment accounted for household energy use, small scale applications, and the logistical and economic constraints specific to BECCS.

Main sources: IDAE,"Evaluación del potencial de energía de la biomasa. Estudio Técnico PER 2011-2020"[33]; AGROALNEX project's report "Evaluación de biomasa potencial en España a nivel provincial" (2023)[34]; INE, Environmental accounts: Waste account (2023)[35]; IDAE, "Uso energético de la biomasa, el biogás y los residuos. Situación en España, 2021 - Abril 2025"[32]; RACVE (Royal Academy of Veterinary Sciences), Livestock farming and Environment[36].

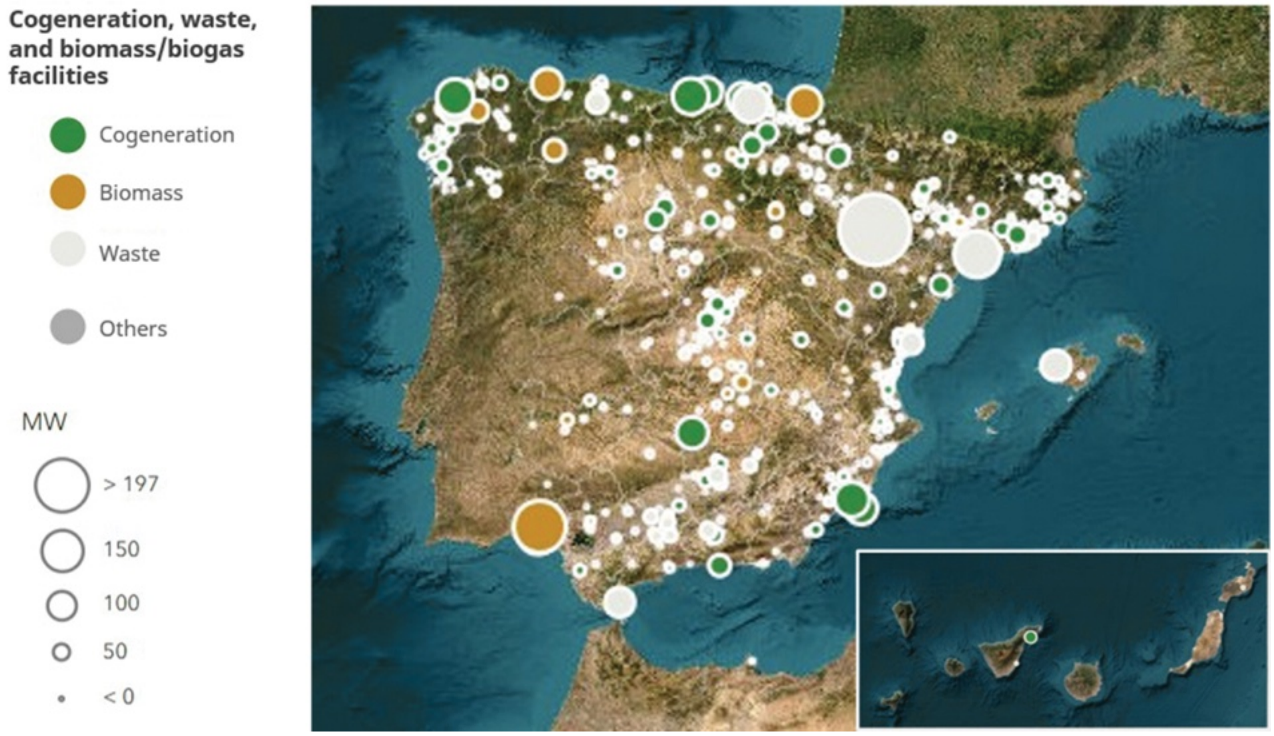


Figure 17. Cogeneration, waste, and biomass/biogas facilities in Spain. Sourced from Red Electrica Española (REE)[37].

or less biodegradable residues. Their development could diversify the bioenergy portfolio and yield carbon-rich products like biochar, supporting CO_2 removal and soil improvement.

Currently, Spain has **no commercial biomass plants operating with CO_2 capture**, as the country lacks commercial operational CO_2 storage. However, several early-stage projects are exploring CO_2 capture from biogenic sources, mainly for utilising CO_2 rather than permanently storing it. Examples include the La Robla Green project in León, which plans to integrate CO_2 capture into a new 50 MW biomass cogeneration plant[39], and Magnon Green Energy's initiative in Huelva, aiming to capture biogenic CO_2 for renewable fuels production such as e-methanol[40].

3.6.1 Biomass scenarios

Spain's diverse biomass resources offer significant potential, with an estimated theoretical potential of **~50 Mt** of dry matter (MtDM) **available for CDR by 2050** (Figure 18). Key feedstocks include livestock manure and slurry suitable for BECCS with anaerobic digestion, followed by agricultural and forestry residues suitable for BECCS with combustion with CO_2 capture, and biochar production via pyrolysis.

Based on Spain's current biomass and residue availability, future developments are expected to follow broader EU trends, pointing to a diversified feedstock mix, where growth in agricultural residues and improved waste collection is offset by stricter sustainability limits in forestry biomass[41].

- **Forestry biomass** is expected to remain at similar levels or decrease marginally (-5% to 0%), reflecting sustainability constraints on stemwood harvest, forest residue mobilisation and lower water availability.
- **Agricultural biomass** is expected to expand slightly (+4-8%), supported by better collection systems and the controlled mobilisation of pruning residues.
- **Agro-industrial residues** are projected to remain broadly stable, as they are tied to crop processing volumes.
- **Biogenic waste** is expected to contribute more significantly by 2050 (+4-10%), driven by improvements in waste management and separate collection systems.

According to these developments, the 47 MtDM of biomass estimated by 2030 (Figure 18), could rise slightly to around **~50 MtDM by 2050** (a 5–6% increase), which is the amount estimated to be available for CDR in the theoretical potential. Spain's biomass potential is expected to remain largely stable, providing a steady but limited feedstock for future bioenergy and CDR pathways.

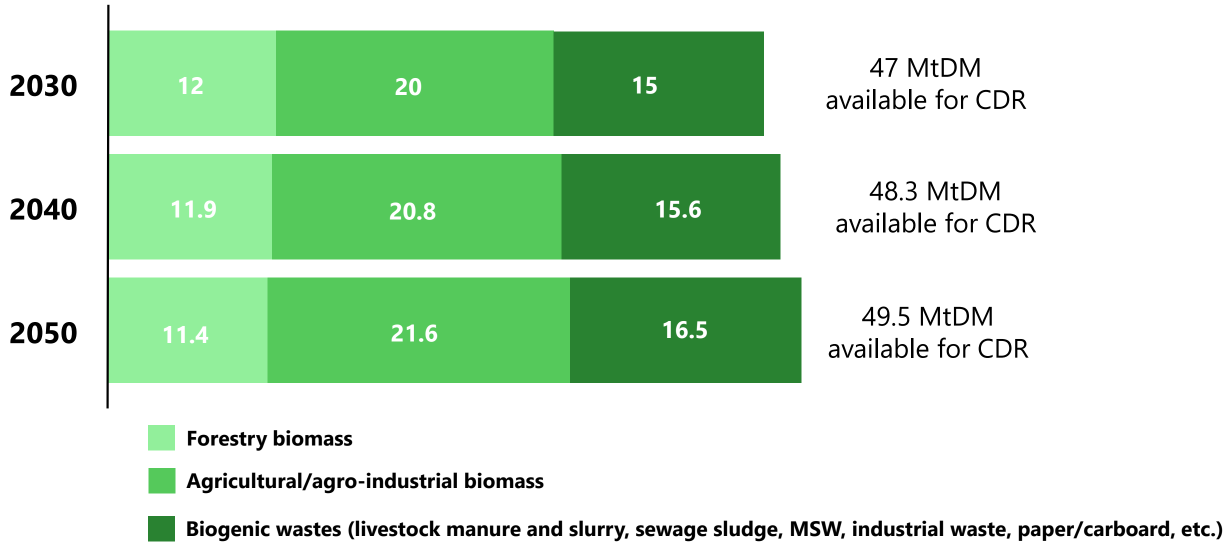


Figure 18. Theoretical available biomass for CDR for 2030, 2040 and 2050 broken down by category[36]. Estimates for 2040 and 2050 apply the proportional EU growth trend by category.

Among the different categories, forestry and agricultural waste are expected to be used in a variety of ways as feedstocks for combustion, gasification or pyrolysis systems integrated with CO_2 capture.

There are plans such as the "Biogas Roadmap"[42] and other studies that foresee growth in biogas/biomethane production. Therefore, livestock manure and slurry are expected to continue to be an important source of biomass, representing one of the most relevant feedstocks for BECCS applications in Spain.

Other relevant biomass sources such as municipal waste, urban and agri-food wastewater treatment sludge among others, provide further biogenic material that could be valorised for energy and carbon capture purposes.

Overall, these highlight a diverse biomass base and potential in Spain offering substantial opportunities for bioenergy and BECCS deployment. However, realising this potential for CDR will depend on improvements in collection systems, regional logistics, competition with other uses (e.g. soil amendment or animal feed), and the development of efficient conversion and capture infrastructure.

3.6.2 CO_2 storage in timber in long-lasting buildings

Structural wood, such as cross-laminated timber (CLT), is a durable bio-based product that stores carbon for the lifetime of a building. In Spain, CLT is the main engineered wood used in construction. According to Mass Madera's 2023–2024 report[43], CLT represented 0.5–1% of new construction in 2022, with potential to reach 1.5–2% at full industrial capacity and ~3% by 2026, driven by forest resources, capacity investments, innovation, and favourable decarbonization policies.

In 2024, about 35 million m^2 of floor area were approved for construction and renovation, with 25.5 million m^2 for new builds[44], the segment where structural wood is most common. Assuming 1.5% CLT use, 0.25 m^3 timber per m^2 built[45], and 0.9–1 tCO_2[46] stored per m^3, **current CLT in buildings is estimated at ~95,500 m^3, storing 0.86–0.95 $MtCO_2$** per year in 2024.

New construction area has remained stable (23–26 million m^2 annually)[47], suggesting steady activity. If **24.5 million m^2** remain constant and CLT use reaches **3%**, carbon stored in timber buildings by **2030** could be approximately **183,750 tCO_2**.

However, the available **data and projections are insufficient to provide robust estimates** of carbon storage in timber buildings **for the years 2040 and 2050**. Due to the long-term nature of these forecasts and the uncertainties surrounding future trends in construction, industrial capacity, and policy developments, the estimates would not be reliable.

For practical purposes, and to ensure consistency in the calculations presented in the subsequent chapters of this report, the estimated value for 2030 has also been used as a proxy for the years 2040 and 2050 when assessing the CDR potential for each horizon

While the contribution of timber construction to CO_2 storage is growing, the magnitude remains very limited when compared to geological storage options. Even under optimistic scenarios, carbon stored in timber buildings would only reach hundreds of thousands of tonnes per year, whereas geological storage in Spain has a technical potential in the order of hundreds of millions of tonnes annually. Therefore, timber construction should be regarded as a complementary niche solution, contributing to material decarbonisation and circularity, but not as a substitute for large-scale carbon storage strategies such as geological sequestration.

3.7 Mineral feedstocks

A range of mineral feedstocks can play key roles in capturing, storing, or chemically binding CO_2, enabling CDR methods like ERW or OAE and storage methods like ex-situ mineralisation. Among the most relevant are naturally occurring calcium- and magnesium-rich rocks/minerals such as limestone, dolomite, and basalt, which can generate alkalinity, enhance weathering processes or promote mineral carbonation.

Spain also has an additional potential for geochemical CDR methods leveraging mafic and ultramafic bedrocks like dunite, peridotite or harzburgite available at the surface or near-surface[48]. Exposed areas only represent multiple thousands of square kilometres, and the CDR potential has been estimated at ~133 $MtCO_2$ removed over a period of 70 years, equivalent to approximately 1.9 $MtCO_2$/year on average. Yet, accessing these rocks would require opening new mines while most of the considered areas are currently under environmental protection regimes.

The dissolution of these rocks in contact with CO_2 and water stores the carbon into stable ions, providing a permanent form of carbon storage. For effective kinetics, the rocks/minerals must be ground to fine powders, increasing the reactive surface area. While the whole rocks could be ground on purpose for CDR, this process is energy-intensive, reducing the overall efficiency of the process from a life cycle analysis point of view. Mining operations, as well as the crushing of these rocks to aggregate size already generates streams of fine particles that are often unused and represent low hanging fruits for CDR applications in the near term.

Industrial byproducts like steel slag or cement kiln dust (CKD) may also serve as supplementary mineral sources for CDR applications, although with additional challenges linked to higher toxicity. These feedstocks result from the production of steel and cement with average rates of 15–20%, respectively. We therefore look at the projected trends for steel and cement production to estimate the potential availability of these by-products.

The **waste fractions of mineral feedstocks suitable for CDR** were estimated in this study at 20-25 Mt of limestone residues, **2.3–2.9 Mt** of dolomite residues, **0.08 – 0.25 Mt** of basalt residues, and **2.58 Mt** cement residues, providing fine-grained material ready for soil or coastal application. By 2050, mineral production could remain at 157 Mt (BAU) or increase to 268 Mt (growth scenario), mainly driven by construction demand. Industrial residues such as **1.9-2.5 Mt** of steel slags also represent a promising feedstock stream.

3.7.1 Current mineral availability

Spain produces significant volumes of minerals suitable for CDR. In 2023, production included **89.3 Mt of limestone, 10.5 Mt of dolomite and 1.7 Mt of basalt**[49]. The cutting and/or handling of these materials generates fine particles that, at present, are mostly a waste product but can be used for CDR.

Figure 19 shows historical production volumes of limestone, dolomite, and basalt. Overall, data reflects an upward trend in the availability of these materials over time, supporting the potential scaling of ERW over the coming decades. In 2023, limestone represents the dominant feedstock, accounting for approximately 82% of total production, followed by dolomite with 10%, and basalt with around 1%.

Spain is a net exporter of these minerals: limestone imports are negligible, while in 2023, basalt and dolomite exports exceeded imports by 21% and 783%, respectively[50,51,52]. The extraction of these minerals is expected to reach lower environmental impacts than metal mining and requires no toxic processing, reducing barriers to expansion. However, the effect of treatment and transportation should be considered.

The geographic distribution of these minerals across Spain is shown in Figure 20. Geographically, the most promising areas for ERW due to resource availability include Galicia, Canary Islands (basalt) and Andalucía (limestone and dolomite).

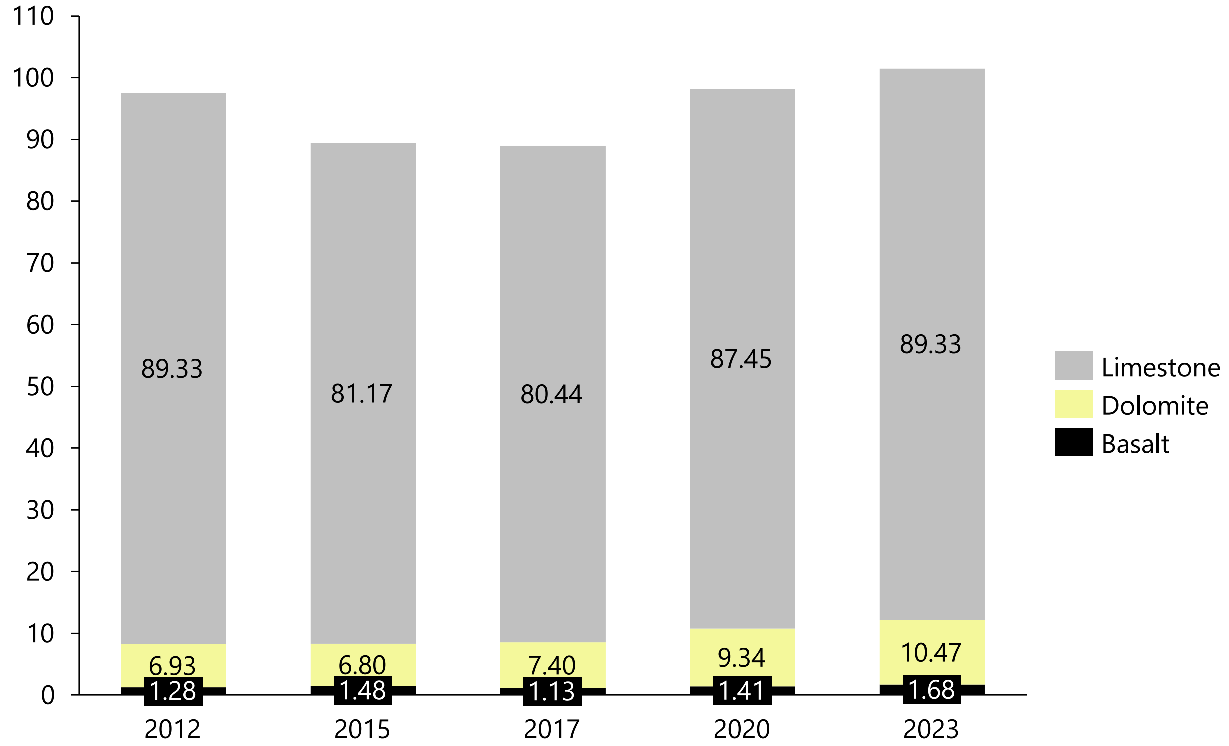


Figure 19. Historical production volumes of limestone, dolomite, and basalt[49].

Steel production in Spain fluctuated between **11 and 14 Mt** per year from 2019 to 2023[54]. As an underused byproduct, steel slag can serve as a promising feedstock for CDR. Given that slag typically accounts for 15–20% of steel output, current production levels yield approximately **1.65 to 2.8 Mt** of steel slag annually[55]. Data on projections was not found.

Cement production has been slightly increasing to **19 Mt** in 2023. Considering a conservative ratio of 150 kg of CKD per tonne of cement produced, we estimated CKD total availability at **2.85 Mt**. No official information was identified on the current uses of cement kiln dust (CKD) in Spain. In practice, CKD is expected to be largely reintegrated into the cement production process, where technically feasible.

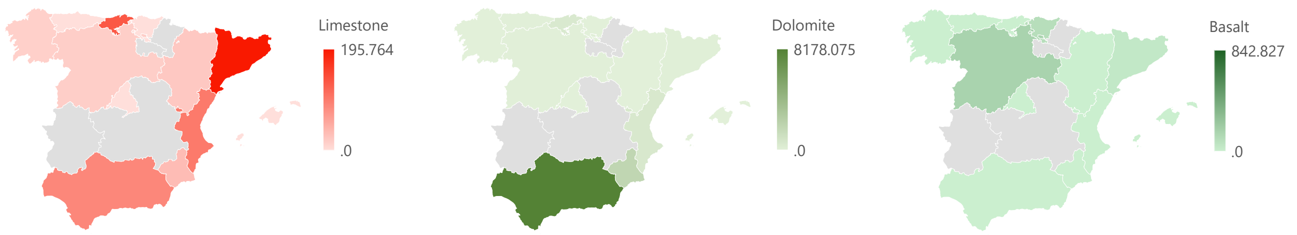


Figure 20. Geographical distribution of production volumes of limestone dolomite, and basalt in Spain in 2022[53]. Data in kt.

3.7.2 Mineral availability scenarios

No recently published scenarios/data were found projecting the production of the considered minerals/rocks into 2050. Hence, two simple scenarios for mineral production are considered, mostly **dependent on the growth of the construction sector**.

- The first scenario is a BAU scenario, which considers a linear growth based on historical data from 2012 to 2023, assuming no political or economic factor trigger any significant change in production or demand. This scenario reaches a total mineral production of **157 Mt** by 2050, with limestone, dolomite, cement, basalt, and steel slags contributing 98 Mt, 23 Mt, 29 Mt, 2 Mt, and 14 Mt, respectively (lower end of range in Table 7).
- The second scenario is a high production scenario that assumes a 3% annual increase in the construction sector from 2023 onwards[56] (which considers rising foreign investment, lower inflation, increased building permits, and major public spending on green and infrastructure projects), leading to a total mineral production of **268 Mt** by 2050, with limestone, dolomite, cement, basalt, and steel slags contributing 198 Mt, 27 Mt, 42 Mt, 4 Mt, and 28 Mt, respectively (higher end of range in Table 7).

3.7.3 Mineral potential for CDR

In this report, **it is assumed that only waste generated when cutting/crushing minerals** (i.e. stone waste) **and slags will be available for CDR**. This aligns with other studies[57,58] that conceive these by-products as promising short-term options for ERW in Spain due to their fine grain size, chemical composition, and proximity to industrial and agricultural zones.

Parameter	Limestone	Dolomite	Basalt	Cement/CKD	Steel/slag
Production (Mt)					
Present	89.3	10.5	1.7	19	12.4
2030	91.2 – 109.9	12.9 – 15.4	1.7 – 2.1	21.2 – 23.4	12.6 – 15.2
2040	94.7 – 147.6	17.3 – 21.3	2 – 2.8	25.2 – 31.4	13.1 – 20.5
2050	98.3 – 198.4	23.3 – 27	2.3 – 3.7	29.3 – 42.4	13.6 – 27.5
Waste generation (Mt)					
Waste rate	22.5 – 28%	22.5 - 28%	5 – 15%	15%	15 – 20%
Present	20.1 – 25	2.4 – 2.9	0.08 – 0.25	2.9	1.9 – 2.5
2030	20.5 – 30.8	2.9 – 4.3	0.08 – 0.31	3.2 – 3.5	1.9 – 3.1
2040	21.3 – 41.3	3.9 – 5.9	0.10 – 0.42	3.8 – 4.7	2 – 4.1
2050	22.1 – **55.6**	5.3 – **7.6**	0.11 – **0.56**	4.4 – **6.3**	2 – **5.5**
Waste recollection (Mt)					
Present	2	0.2	0.008	uncertain	uncertain
2030	2.05	0.3	0.01	uncertain	uncertain
2040	2.13	0.4	0.01	uncertain	uncertain
2050	2.2 – 5.56	0.5 – 0.7	0.01 – 0.05	uncertain	uncertain
Other issues					
Suitability	Ocean liming, soil amendments	Ocean liming, agriculture	Agricultural field spreading	Ocean liming, agriculture	Agricultural mixing
Potential obstacles	Calcination and/ or pulverisation needed	Industrial prioritisation	Limited production	Waste management	Regulation, distributed locations

Table 7. Estimated production and residue of key mineral feedstocks suitable for CDR.

While the considered minerals are primarily used for construction, a significant fraction becomes available as fine-grained residues during cutting and processing. Residue rates vary by mineral type and are estimated to range between 22.5% and 28% in the case of limestone or dolomite[57,58]. For basalt, the residue rate is estimated to be 5-15%[59].

Table 7 shows the estimated waste generation from minerals feedstock suitable for CDR. Based on shown ranges, the maximum theoretical availability of minerals for CDR was estimated at **27-38 Mt by 2030, 30-51 Mt by 2040**, and **32-69 Mt by 2050**, with the lower values reflecting the BAU pathway and the upper values corresponding to the high production scenario. However, for the realistic scenario, a conservative assumption was made that **10% of the total generated waste fraction of limestone, dolomite, and basalt** is effectively collected as a separate material stream (reflecting operational constraints or internal recirculation), reaching then **2.3-3.8 Mt by 2030, 2.5-5.1 Mt by 2040**, and **2.7-6.8 Mt by 2050**. Forecasts on steel slag generation assumed that future steel production would increase at the same pace of cement as these industries are highly correlated. For CKD and steel slags, the waste recollection fraction used for CDR may be uncertain given the technical limitations in facilities, asl well as the current and or potential uses of these waste streams.

Near-term pilot projects could focus on stone-cutting residues and steelmaking slag, which require minimal extraction. Advancing this approach demands new logistics, traceability systems, environmental considerations, and business models linking mineral waste to agricultural use. Given the balance between volume and reactivity, low-barrier deployment should prioritise readily available waste materials easily integrated into current agricultural or coastal practices.

3.8 CO_2 storage

Spain has an estimated cumulative potential of 11 $GtCO_2$ in geological formations (i.e. traps)[60], **although it currently lacks operational commercial storage sites**. The Geological and Mining Institute of Spain has identified 85 suitable areas[60], most of which remain at a low level of maturity (SRL 2-4). However, the theoretical storage capacity could increase in the future, as there are storage units with unassessed or unreported potential, mainly due to data confidentiality restrictions and the limited availability of detailed geological information[61].

The most advanced initiative is the TarraCO_2 project[62] in Tarragona, supported by the EU, with a planned capacity of **2 $MtCO_2$ per year from 2030 onwards** and a maximum storage potential of 54 $MtCO_2$, subject to technical viability and ministerial authorisation. Theoretical CO_2 storage potentials through in-situ mineralisation (~1.8 $GtCO_2$ cumulative capacity in mafic–ultramafic rocks) and ex-situ routes (~7.7 $MtCO_2$/year from alkaline industrial wastes) exist in Spain; however, both are expected to be **considerably reduced** in practice due to factors such as accessibility, reaction kinetics, water availability, infrastructure, and social acceptance. In the case of ex-situ mineralisation, the 7.7 $MtCO_2$/year estimate also includes other geochemical routes (like ex-situ OAE and ocean liming, ERW and mineral carbonation of alkaline-rich materials, and electrochemical separation processes), meaning that the strictly mineralised fraction would be even smaller.

It is important to clarify that, although this report refers to projects, geological storage capacities, and infrastructures that are currently conceived and developed mainly for carbon capture and storage from industrial sources (CCS), in reality, these same infrastructures could be used in the future to manage CO_2 captured through carbon dioxide removal methods such as BECCS or DACCS. While CCS and CDR are distinct concepts, the former referring to the capture of CO_2 from industrial point sources and the latter to the removal of atmospheric CO_2, both require similar infrastructures for the safe and permanent transport and storage of CO_2. Therefore, the existence and development of this infrastructure is relevant to both approaches. In fact, in the future, all CO_2 sources in the country (whether from CCS or CDR) will compete for access to the same storage sites and transport infrastructure. For this reason, it is essential to mention and analyse these infrastructures in the context of CDR, even if they are currently only being considered for CCS.

At present, there are no projects or infrastructures in Spain specifically dedicated to CDR, so to analyse the realistic potential for CDR deployment, it is necessary to work with the available information, which for now is limited and focused on CCS. This approach makes it possible to identify the real opportunities and limitations for the future deployment of CDR, based on the premise that infrastructure developed for CCS can be leveraged, adapted, or expanded for the management of CO_2 captured by CDR methods.

3.8.1 Geologic CO_2 storage

Spain has taken some steps in developing geological carbon storage, notably by ratifying the 2006 amendment to the London Protocol[63] enabling CO_2 storage beneath the seabed.

The European Commission has promoted a series of strategic initiatives, in which Spain has participated, aimed at advancing the identification of suitable areas for underground CO_2 storage, notable among these are the CO_2Stop[c] and Hystories projects[61], whose data has been integrated into the GSEU (Geological Storage for Europe) project. This latter initiative has led to the creation of a harmonised geological database for the entire continent and has resulted in the Pan-European GCS Atlas[64], a valuable technical and strategic cartographic tool. The Atlas represents storage potential through three nested layers[61]:

- **Formations:** large porous and permeable rock zones meeting national geological criteria.
- **Storage units:** deeper (>800m) sections within formations, suitable for keeping CO_2 in a supercritical state and capped by impermeable rock to ensure storage integrity.
- **Traps:** specific geological structures like domes or depleted hydrocarbon reservoirs that securely confine CO_2 and serve as key targets for storage capacity and maturity assessments. Traps, therefore, are the most detailed level of analysis.

Although **Spain currently has no commercial operational geological CO_2 storage sites**, its theoretical storage capacity is estimated at around 11 $GtCO_2$ (IGME, 2024)[60] across 75 traps in saline aquifers and 10 in depleted hydrocarbon fields. These traps are unevenly distributed, with central and northeastern regions showing the most promise (see Figure 21). Additional uncharacterised units may raise this estimate, though data gaps and confidentiality limit current assessments[36].

Other studies, such as by Clean Air Task Force (2023)[65], suggest a broader range of 12-44 $GtCO_2$, reflecting the high degree of uncertainty in current geological knowledge. In this study, the Ebro Basin stands out as one of the most promising regions for future large-scale geological CO_2 storage. This area includes major industrial clusters such as Tarragona and southern Aragón, and contains deep

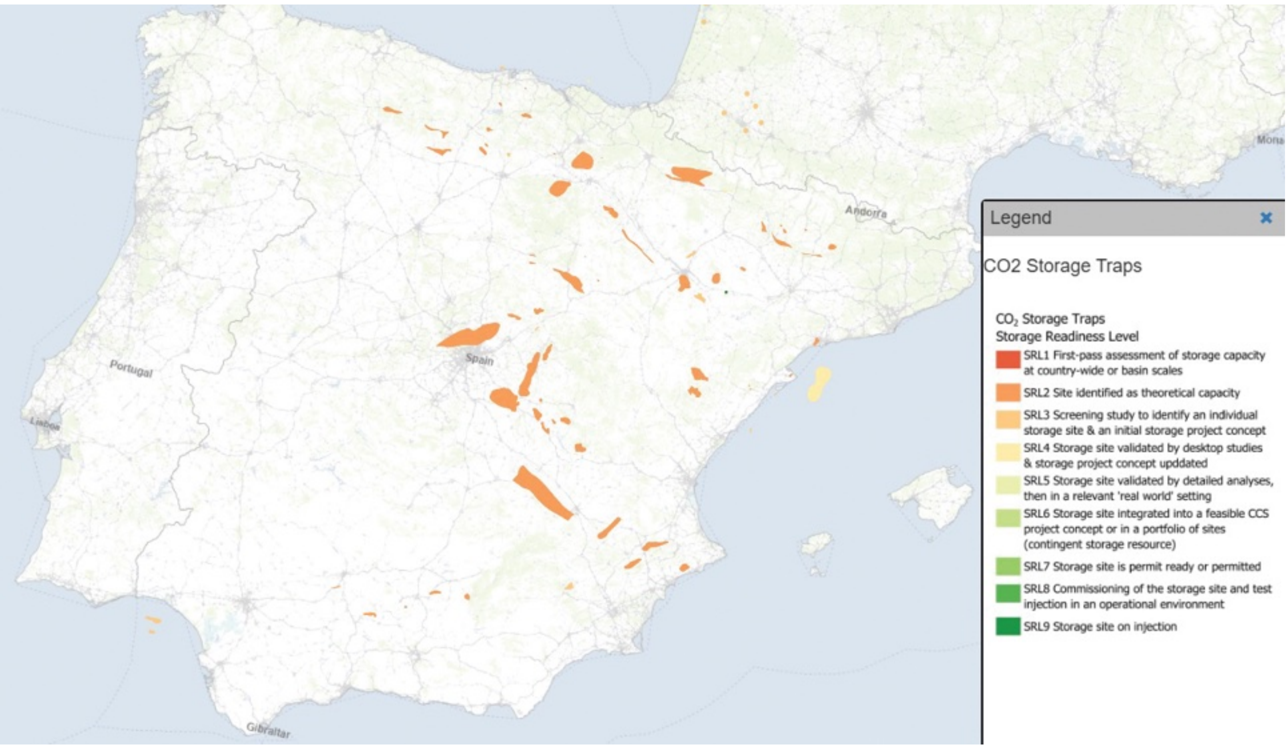


Figure 21. Geological reserves for carbon storage in Spain (Canary Islands excluded from the illustration as they have no identified storage potential)[64].

c. CO_2Stop project established a methodology that combines volumetric models to calculate the available pore volume, along with the application of sweep efficiency, saturation factors, and CO_2 density under reservoir conditions.

saline aquifers both onshore and offshore that have been preliminarily shortlisted as suitable storage formations. According to recent assessments, the basin could offer an estimated effective storage capacity of approximately 0.85-1 Gt CO_2[66].

Although there are currently no commercial CO_2 storage facilities in operation, there is an active pilot-scale research site dedicated to the development and validation of geological storage methods. In this context, the *Hontomín* Technology Development Plant (TDP), located near the city of Burgos in Spain, serves as a reference experimental site and is recognised by the European Parliament as a key testing infrastructure for geological CO_2 storage. Managed by Fundación Ciudad de la Energía (CIUDEN), it constitutes the only active onshore CO_2 injection facility in the European Union, operating exclusively for research, testing and monitoring purposes[67].

The facility is built over a deep geological reservoir accessible through two vertical wells of approximately 1,570 metres in depth. It features cryogenic storage systems capable of holding up to 150 tonnes of CO_2 and supports controlled injection operations at flow rates of up to 2 kg/s, supported by advanced hydrogeological and seismic monitoring networks that enable continuous assessment of subsurface behaviour. The infrastructure also comprises a CO_2 conditioning system and a modular building equipped for operational control and technical supervision[68]. Multiple research and testing campaigns have been carried out, mainly funded through European R&D programmes[69] such as OXYCFB300, IMPACTS and ENOS, which underline the strategic relevance of Hontomín as a pilot hub for advancing scientific and technological knowledge in geological CO_2 storage and monitoring.

To guide development, the European Commission uses the Storage Readiness Level (SRL) framework[d,61], which ranks sites by technical maturity, documenting progress and remaining steps within CCS projects. As shown in Figure 19 most reservoirs in Spain are at SRL 2 (early stage), except the offshore TarraCO_2 site, which has reached SRL 4 (equivalent to when a research permit is requested). Overall, capacities have not yet been fully demonstrated, and further studies are needed.

TarraCO_2, led by Repsol, aims to store CO_2 45 km off Tarragona's coast. Backed by €205 million from the EU Innovation Fund, the project **targets 2 MtCO_2/year by the end of 2030**, with a total capacity of 54 MtCO_2[62]. It is also set to support a CCUS ecosystem in the Tarragona industrial hub, where over 6 Mt of emissions are generated annually within a 120 km radius by sectors such as cement and chemical production. The EU funding is meant to support the deployment of innovative decarbonisation methods, including CCUS, but has not yet received the final authorisation from the Ministry for Ecological Transition, which will allow its technical viability to be assessed. It should be noted that the granting of this European aid does not oblige the project to be implemented, which will only go ahead if its technical and economic viability is confirmed and it has the necessary institutional and social support[62].

Another project worth highlighting is being advanced by the energy company Nexwell[70] from the United States, which has applied for a research permit to develop a large underground CO_2 storage site in the Maestrazgo region. The permit request covers 13.5 kha across several municipalities, with an estimated storage cumulative capacity of around 100 MtCO_2, making it one of the largest potential facilities in Spain. The studies are expected to last five years, with possible exploitation in the next decade. Nexwell has also applied for a research permit to characterize a potential CO_2 storage site in the Region of Murcia (Moratalla and Cehegín)[71], preliminarily assessed as capable of storing 366 Mt CO_2. The project, developed in collaboration with the Polytechnic University of Cartagena, is currently in the geological characterization phase and aims to assess the technical feasibility of the site.

Nevertheless, the current reality shows significant political and social opposition in the territory[72], driven by perceived environmental risks and concerns about the development model associated with such projects. In addition, at the national level, deployment will take time and there is no strong momentum in the short term. This underlines the importance of transparent, rigorous, and participatory communication to build social trust and frame the debate with clear and accessible information.

To unlock Spain's storage potential, targeted investment is essential. The construction of storage sites requires high upfront capital and long payback periods, making it necessary to design public-private financing mechanisms that mitigate risk and build investor confidence. Encouraging geological storage projects and facilitating access to licenses and seismic data will help create a more favourable environment for their large-scale deployment.

d. SRL considers factors such as geological knowledge, technical validation, exploration history, and data availability.

Box 3. Methodology to estimate geological CO_2 storage

As shown in Figure 21 and in the corresponding database of the IGME[64,e], high-quality information is not available for all the storage sites on the map. For this reason, the analysis of the theoretical and realistic CO_2 storage scenarios is based on the following methodology, which classifies the sites into three risk levels: low, medium, and high.

Low risk. Currently, the only storage site under development - although still pending exploration permits - is TarraCO_2, with an estimated total cumulative capacity of 54 MtCO_2. Therefore, this site is considered the only low-risk option.

Medium risk. Although no detailed feasibility studies have been carried out, the Maestrazgo and Murcia areas present high storage potential, and research permits have recently been requested to begin studying them. According to the preliminary IGME database, their estimated average cumulative capacities are approximately 132 MtCO_2 and 200 MtCO_2, respectively.

High risk. The capacities assigned to high-risk storage sites differ depending on whether the theoretical or realistic scenario is considered:

- The **theoretical scenario** includes all storage sites in the database that have acceptable quality data and high-quality data - excluding TarraCO_2, Maestrazgo, and Murcia, which are already accounted for in the low and medium-risk categories, and the Hontomín pilot storage site as it is not a commercial facility. Under these criteria, the total cumulative capacity amounts to approximately 11.7 GtCO_2 (1.5 GtCO_2 for sites with high-quality data and 10.2 GtCO_2 for sites with acceptable-quality data).
- The **realistic scenarios** include only storage sites with high-quality data, maintaining the same exclusions applied in the theoretical scenario (TarraCO_2, Maestrazgo, Murcia, and Hontomín, which are accounted in the low and medium-risk categories). With this, the total storage capacity is 1.5 GtCO_2.

Based on the methodology, a risk adjustment factor (RAF) has been applied to each category to adjust the estimated capacity according to the level of risk and, therefore, the degree of uncertainty associated with its viability. The RAF has been determined based on the available information on storage sites, considering factors such as the level of studies, planned projects, and data quality. Table 8 below shows the RAF values considered in each case.

On this basis, the cumulative storage capacity expected to be available in the 2030, 2040 and 2050 time horizons was determined. To this end, realistic assumptions have been made regarding the pace of storage site development in Spain, considering the current maturity of the projects, the availability of data, and the time required for exploration, characterisation, permitting, and commissioning.

In **2030**, only the TarraCO_2 storage site is assumed to be operational, as it is the only one currently under development. This results in a cumulative theoretical storage capacity of 48.6 and a realistic of 43.2 MtCO_2 in 2030. By **2040**, the landscape is expected to broaden with, in addition to TarraCO_2, the Maestrazgo and Murcia storage sites becoming operational, both classified as medium risk and with significant preliminary capacities. During this same period, it is assumed that about half of the potential capacity from high-risk storage sites may be available, as some could mature technically between 2030 and 2040 while others may not, due to uncertainties in data quality and viability. This results in a cumulative theoretical storage capacity of 1189.85 and a realistic of 288.61 MtCO_2 in 2040. By **2050**, the entire storage capacity is expected to be available. This outlook rests on the assumption that continued research, detailed site studies, and the accumulation of operational experience will collectively enable the safe and reliable deployment of all facilities over the long term. This results in a cumulative theoretical storage capacity of 2081.6 and a realistic of 717.8 MtCO_2 in 2050.

e. For all storage sites analysed, the estimate 'EST STORECAP MEAN (Mt)' has been used instead of the maximum capacity estimated in the database, to adopt a conservative approach. This variable corresponds to the 'Mean estimated CO_2 storage capacity (Mt) – aquifer daughter unit only'.

Storage sites	Low risk TarraCO$_2$	Medium risk Maestrazgo and Murcia	High risk High quality data Other saline aquifers and hydrocarbon traps	Acceptable quality data	Total cumulative capacity ($MtCO_2$) 2050
Cumulative storage capacity	54	332.66	1527.9	10,195.55	
Risk Adjustment Factor (RAF) - Theoretical	0.9	0.75	0.5	0.1	
Risk Adjustment Factor (RAF) - Realistic	0.8	0.65	0.3	0	
Cumulative theoretical storage capacity ($MtCO_2$) with theoretical RAF applied	48.6	249.5	763.95	1019.56	**2081.6**
Cumulative theoretical storage capacity ($MtCO_2$) with realistic RAF applied	43.2	216.23	458.37	0	**717.8**

Table 8. Risk classification of storage sites in Spain and their cumulative storage capacity, theoretical and realistic with RAF applied.

The estimate of theoretical CO_2 injection in 2050 can be found in Chapter 4.2, and the realistic annual injection in Chapter 7.

3.8.2 CO_2 storage through carbon mineralisation

Spain has significant potential for CO_2 storage through mineralisation, both in-situ (injection into mafic and ultramafic formations) and ex-situ (utilization of industrial residues and alkaline by-products). The country's diverse geology, with accessible mafic and ultramafic rocks in regions such as Galicia, Andalucía, Murcia, and the Canary Islands, offers promising sites for in-situ CO_2 storage via mineral carbonation, with around 1.8 Gt CO_2. At the same time, the annual production of industrial alkaline wastes and by-products provides a substantial resource base for ex-situ mineralisation, amounting to about 7.7 $MtCO_2$/year.

While the theoretical maximum potential is considerable, the realizable capacity will depend on overcoming practical constraints such as material accessibility, reaction kinetics, infrastructure development, and social acceptance. Continued research, pilot projects, and supportive policy frameworks will be essential to unlock and scale up Spain's mineralisation-based CDR, enabling it to make a meaningful contribution to national and European climate targets.

In-situ mineralisation

The theoretical cumulative storage potential for in-situ mineralisation in mafic-ultramafic rocks is estimated at around **1.8 $GtCO_2$**[73], although practical constraints (accessibility, reaction kinetics, water resources, infrastructure, and social acceptance) substantially reduce the realisable resource.

Drawing on international experience (CarbFix, Wallula, Coda Terminal) and the expected pace of project deployment, Spain's annual mineralisation potential is estimated at **0.1–0.2 $MtCO_2$** by 2030, **0.4–0.8 $MtCO_2$** by 2040, and **0.8–1.5 $MtCO_2$** by 2050 (Figure 22). These estimates assume an initial phase in 2030 with one coastal hub (e.g., Canary Islands) and one mainland pilot, together hosting 6–10 wells delivering 15–20 kt CO_2/year each. By 2040, scaling to two operational hubs with 20–30 wells at 20–25 kt/year would raise capacity to 0.4–0.8 Mt/year. Reaching 2050, 2–3 hubs and 40–60 wells at similar injection rates would enable 0.8–1.5 Mt/year of mineralised CO_2. Injection rates are based on international pilots such as CarbFix (Iceland)[74] and Wallula (USA)[75], where wells typically mineralise 15-25 kt of CO_2 per year. The well numbers reflect a gradual scale up aligned with expected permitting timelines, infrastructure development, and the availability of suitable geology and CO_2 sources in Spain.

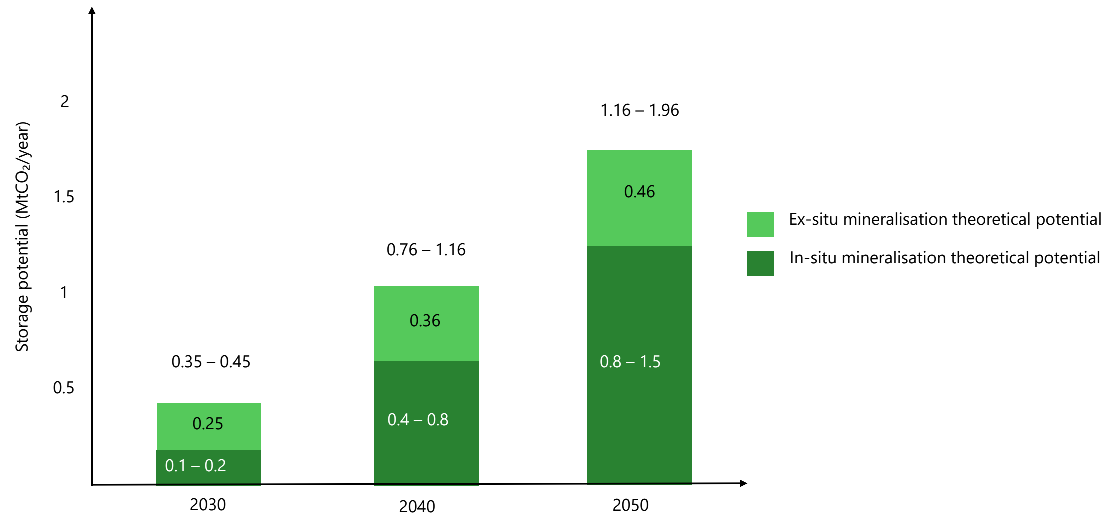


Figure 22. In-situ and ex-situ theoretical potential.

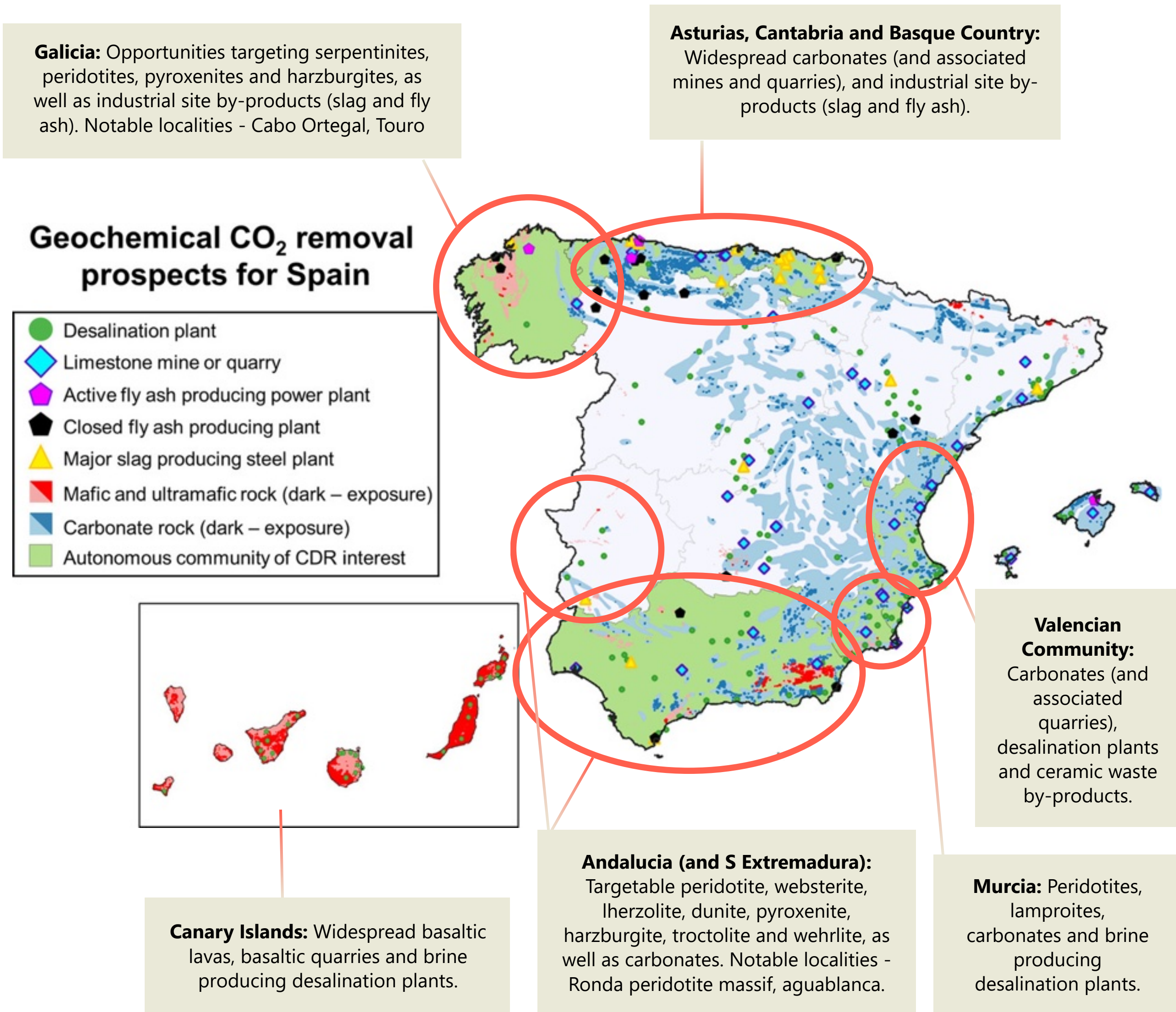


Figure 23. Map highlighting targetable areas for geochemical CDR projects and approaches in Spain[76].

These values assume the progressive commissioning of several mineralisation hubs in regions such as Galicia, Andalusia, and the Canary Islands, the use of seawater for dissolved CO_2 injection, and the integration of industrial CO_2 sources and DAC methods. The upper range would only be achievable with strong industrial policy, infrastructure development, and favourable social acceptance.

The most promising locations for mineralisation in Spain are the accessible mafic and ultramafic rock formations found in regions such as Galicia, Murcia, and Andalucía - including peridotites, serpentinites, dunites, harzburgites, and basalts. Additionally, the Canary Islands, with their extensive basaltic and basanitic lava units, present significant opportunities for geological storage (Figure 23).

Ex-situ mineralisation

Spain's ex-situ mineralisation potential from industrial alkaline wastes and by products is estimated at **up to 7.7 $MtCO_2$/year**[76] for combined geochemical pathways, though the strictly mineralised share would be lower. At present, mineral carbonation activity remains limited. A notable example is AggregaCO_2, a pilot project by Petronor, O.C.O and REPSOL group partners, which has achieved around **2,200 tCO_2/year** of mineralised CO_2[77].

To reflect current realistic potential, this assessment considers only the most suitable waste streams - fly ash, cement kiln dust, and steel slag. Considering that the study "Geochemical carbon dioxide removal potential of Spain"[73] estimates an availability of around 5 Mt of these by-products per year, and with a CO_2 uptake of 50 kg CO_2 per tonne of industrial by-product, a potential of **0.25 $MtCO_2$** is estimated for **2030**. As industrial residue collection, processing, and mineralisation technologies scale, this potential could grow to an annual potential of **0.36 $MtCO_2$** in 2040 with broader deployment and process optimisation, and **0.46 $MtCO_2$** by 2050, assuming mature implementation and most suitable residues being mineralised.

3.8.3 Conclusion on CO_2 storage

Spain possesses significant geological potential for CO_2 storage; however, the absence of a defined national strategy, together with limited pilot-scale development, has slowed its advancement in this field.

To enable large-scale deployment, it is essential to establish robust public–private financing frameworks, accelerate and simplify permitting and regulatory procedures, and reinforce geological characterisation efforts to reduce current uncertainties and increase investor confidence. In parallel, international cooperation mechanisms will be required, including bilateral agreements for cross-border CO_2 transport and storage, particularly with countries already equipped with mature storage infrastructure.

The combination of these actions would lay the foundations for a viable, secure and competitive carbon management system, positioning Spain as an active participant in the European decarbonisation agenda while leveraging its own geological resources for climate mitigation.

3.9 CO_2 infrastructure

CO_2 infrastructure is fundamental to the large-scale deployment of CDR methods, ensuring the safe and cost-effective transport and storage of captured carbon dioxide. Although the CO_2 infrastructure projects mentioned in this section are currently designed for CCS applications, they are expected to be adaptable in the future to handle CO_2 captured through CDR methods, such as BECCS and DACCS. This flexibility would enable these systems to support broader carbon removal strategies, leveraging existing investments to accelerate climate mitigation efforts.

The COMET project (7th EU Framework Programme, 2010–2012[78] was the first integrated study on the infrastructure required for CO_2 capture, transport, and storage in the Western Mediterranean (Spain, Portugal, and Morocco). It identified emission sources, potential storage sites, and the most cost-effective transport modes -pipelines, ships, trains, or trucks.

3.9.1 Pipelines and export terminals

To date, Spain does not have any operational CO_2 export terminals or pipelines, but several studies are exploring the use of existing Liquified Natural Gas (LNG) terminals for this purpose, given their strong technical and infrastructural synergies with CO_2 handling. These facilities could be adapted into multi-molecule platforms, using residual cold from regasification for CO_2 liquefaction and taking advantage of existing port, storage, and safety infrastructure. Moreover, the expertise of LNG terminal operators in managing cryogenic gases provides a solid foundation for the safe and efficient development of future CO_2 export capabilities.

Many LNG terminals are in industrial areas with significant CO_2 emissions, enabling direct integration with capture and transport systems. At the same time, they are embedded within well-developed service and logistics networks that could potentially be used or adapted to link capture sites with export hubs. Spain has 7 LNG export terminals and some of these terminals are already being considered as strategic locations for the future development of CO_2 terminals such as those in El Musel (Gijón)[79], Bilbao[80], and Sagunto[81].

Enagás, Spain's main gas system operator, has identified six priority regions for CO_2 capture and transport projects (Figure E.2 in Annex E). The company is developing hubs in these areas to enable CO_2 capture, transport, and storage infrastructure within Spain and/or for export and storage abroad. Hub-based projects allow emission aggregation and cost optimisation.

As of July 2025, the following are some of the planned CO_2 infrastructure development projects involving LNG terminals that are public:

- **CO_2NECTA (Valencia)**: at Holcim's Port of Sagunto site, CO_2 will be captured and piped 7 km to the Sagunto LNG terminal for liquefaction and storage (0.8 $MtCO_2$)/year). Led by Enagás, Holcim, and Saggas. Construction is expected to start between 2028 and 2029. Operation: 2031-2032.
- **MOSUSOL-NETCO_2 (Catalonia)**: this project will capture CO_2 from the Molins cement plant and transport it through a 100 km pipeline to offshore storage near the Port of Tarragona (over 1 $MtCO_2$/year). Developed by Enagás and Molins, it aligns with an existing underground storage concession and targets operation between 2031–2032.
- **CO_2net2 Norte**: (which is included in the PCI Project in the provisional list of the European Commission): aims to develop a CO_2 transport network in northern Spain, linking emitters in the Basque Country and Asturias and adjacent regions with LNG terminals for liquefaction and export using residual cold from LNG processes (approx. 5 $MtCO_2$/year). The project plans construction in 2029–2030 and operation from 2032. Figure 24 shows the infrastructure part of the project planned in Spain in phases.

3.9.2 Train

The rail network is central to CCUS/BECCS projects, as it is currently the only transport mode that does not require substantial modifications for immediate use. The transport of captured CO_2 by rail is regulated under the RID 2023 framework as a standard dangerous good, requiring no special authorisation and facing only weight-based limits per wagon[82].

Figure 24. Phased infrastructure proposed by Enagás for the CO_2net2 North project.

According to the 2023 *Observatorio del Ferrocarril en España*[83], freight trains operate across 9.147,10 km of Adif-managed track (both Iberian and standard gauge). Of this total, 8,686 km are shared with passenger services and 460 km are freight-only, plus 508 km on metre-gauge lines. Tank wagons enable efficient CO_2 transport along these corridors, with key parameters:

- Average train speed: 120 km/h, suitable for long-distance logistics.
- Maximum weight per four-axle wagon: 90 tonnes, allowing 61.7 tonnes of CO_2 per wagon[16].
- No practical limit on wagons per train: with 20 wagons, a train can carry about 1,220 tonnes of CO_2.
- Unloading rate: 20 tonnes/hour per unit, depending on station equipment.

In this context, a recent agreement between Adif and Exolum (*logistics services company for the transport and storage of fuels, biofuels and liquid fuels*) aims to develop a rail-based logistics network for products like captured CO_2, ammonia, methanol, biofuels, and renewable feedstocks. This initiative seeks an immediate, flexible, low-impact solution by linking Exolum's facilities with Adif's infrastructure. The project, coordinated by the Atlantic Corridor Commissioner, will study capacity, technical feasibility, and potential new sidings to connect production sites with ports. Leveraging Exolum's experience in energy transport and its 17 rail-connected terminals in Spain, the partnership aims to deliver a sustainable, cost-efficient solution using existing infrastructure - minimising environmental impact and avoiding land expropriations.

3.9.3 Truck

Road transport by truck offers flexible CO_2 delivery for local or regional needs, especially where pipelines are absent, requiring minimal infrastructure beyond loading and unloading stations. However, with a limited capacity (0–30 t per tanker), it suits only small volumes and short distances (<300 km)[84]. It is also sensitive to weather and traffic, incurs high and variable costs, and risks congestion in large-scale deployments. For longer distances and higher volumes, pipelines and shipping remain more efficient and scalable alternatives[85].

3.9.4 Shipping

Maritime transport of CO_2 is becoming a strategic option for moving large volumes between distant regions or areas without pipeline connections, and for transferring CO_2 from capture sites to storage locations. The logistics chain involves four stages: **capture and conditioning, liquefaction and storage, maritime transport in specialised vessels, and injection into geological formations**.

Currently, ship-based CO_2 transport is limited to small-scale uses, but future carbon capture and storage projects will require much larger operations. To reduce costs, transport will likely follow conditions similar to LPG carriers: 7–9 bar pressure and –50 °C, or slightly higher pressures with temperatures near –30 °C[86]. Safety is governed by the International Gas Carrier (IGC) Code, which provides a robust regulatory framework for CO_2 transport by sea[87].

It is worth noting that Enagás[88] announced the launch of *Scale Green Energy*, a subsidiary aimed at promoting decarbonisation infrastructure and services in areas such as LNG/BioLNG bunkering, renewable hydrogen, and CO_2 management. The latter includes the development of CO_2 pipelines, liquefaction plants, and transport vessels, with projects such as *CO_2necta* together with Holcim and Saggas, and *MOSUSOL NetCO_2* with Molins.

3.9.5 Conclusions on CO_2 infrastructure

Spain has the infrastructure base to support CO_2 transport and export, offering a strategic opportunity to scale CDR methods. **Co-locating CDR facilities near industrial hubs with planned CO_2 infrastructure** would reduce costs, simplify logistics, and accelerate a national CO_2 management value chain. Despite its potential, **Spain currently lags behind other EU countries** in deploying CCS/CDR. The government has yet to launch a dedicated strategy or submit required estimates to the European Commission on capture potential, transport plans, or storage capacity. Spain has also not yet communicated to the European Commission, as required, its estimates for annual CO_2 capture potential by 2030, nor has it provided information on CO_2 transport infrastructure or detailed assessments of its geological storage capacity.

Industry leaders have urged the Ministry for the Ecological Transition to provide clear direction, warning that **without defined transport and storage pathways, investment will stall**. While CCUS inclusion in the updated PNIEC is a step forward, stakeholders continue to call for a roadmap - akin to those for hydrogen and biogas - to prevent industrial decline and capital flight to other countries.

3.10 Restricted areas

A substantial portion of Spain's land and marine territories falls within legally restricted areas - including National Parks, Natura 2000 sites, marine reserves, and other protected zones - covering approximately 27% of terrestrial and nearly 8% of marine environments[89] (Figure E.3 in Annex E). These protected zones impose strict limits on land use, prohibiting activities that could disrupt conservation goals, such as large-scale mining, coastal development, or unregulated spreading of alkaline materials for ERW. From a CDR implementation perspective, this means that while Spain has abundant geological feedstocks, deploying mineral-based CDR within or adjacent to these restricted areas would require careful environmental impact assessments, permitting, and adaptive management to avoid harming sensitive ecosystems.

Given the overlap between high potential geochemical CDR zones and legally protected areas, CDR strategies must adopt deliberate spatial planning to balance carbon removal objectives with biodiversity conservation. Ex-situ approaches - such as using alkaline residue in croplands, greenhouses in Almería, or along railroad embankments - offer more flexibility, reducing conflict with regulations in Natura 2000 or marine protected areas. For coastal applications, OAE presents opportunities outside strictly protected seas, but pilot sites should exclude marine reserves and must comply with environmental monitoring, particularly in Natura 2000 marine habitats. Ultimately, success in restricted zones will depend on integrating CDR pilots with existing land use planning and environmental regulation frameworks, ensuring that CDR deployments enhance rather than undermine Spain's conservation commitments.

4. Theoretical CDR potential (Could do)

To estimate Spain's theoretical CDR potential, the analysis first assesses the maximum availability of relevant resources - such as biomass, land, and energy - while preserving their essential priority uses. This hypothetical scenario assumes full mobilisation of all suitable resources for CDR, without factoring in real-world constraints, competing demands from other sectors, or societal readiness. While not practically feasible, this upper-bound estimate serves as a benchmark for understanding what could be achieved under extraordinary circumstances, akin to a nationwide mobilisation effort to address climate change. This theoretical maximum helps frame the more realistic estimates presented in Chapter 7.

4.1 Methodology for the theoretical CDR potential

To assess the theoretical potential, it is necessary to estimate the availability of each resource needed to implement CDR methods. Most methods rely on multiple inputs - such as electricity, water, or heat – and therefore compete for the same resources. The calculation of theoretical potential is based on a bottom-up approach grounded in the resource-availability scenarios developed in Chapter 3, determining how Spain's physical resources could be allocated most efficiently to maximise overall removal. For each CDR method it is firstly defined what is the primary resource – or resources – needed, and resources are then allocated optimally to the different methods based on which method requires the less resources per net tonne of CO_2 removed. The methodology and database used for this optimisation is described in section 2.3. Based on this allocation, it is then calculated how much of CO_2 could be removed under Spain's most optimistic resource projections using the portfolio of methods in the most optimal way to promote maximal carbon removal.

Energy efficiency and economic feasibility were qualitatively considered in the resource allocation process, though no economic variables were included in the calculations. For example, while biochar is a highly resource-efficient method, its use is capped because diverting most wood based biomass to biochar would exceed market demand and undermine the need for a balanced CDR portfolio. For CDR methods where feedstocks could be clearly assigned without competition from other CDR methods, the CDR potential was calculated by applying conversion factors to translate available feedstocks into equivalent tons of CO_2.

4.2 Theoretical CDR potential in Spain

Spain's theoretical CDR potential is revealed by the optimised allocation of resources to the different removal methods estimated at nearly **~196 Mt CO_2 per year by 2050**. The breakdown of methods and underlying assumptions is shown in Table 9. Electricity and heat were allocated to maximise electrochemical pathways, while ERW was assumed to require negligible energy, using only waste fractions of mineral feedstock. Water and land constraints were not considered for ERW. Overall, the maximum potential is largely limited by CO_2 storage capacity, especially for BECCS and DACCS.

In the theoretical potential, the CDR methods that have the highest removal capacity by 2050 are ecosystem management methods, particularly afforestation and reforestation (50.24 $MtCO_2$) and cropland management (47 $MtCO_2$), together representing more than 66% of the total. Geochemical options, including enhanced rock weathering using industrial residues and mining by-products, contribute around 30 $MtCO_2$, whereas synthetic methods such as DACCS account for a more modest 9 $MtCO_2$, mainly limited by available storage capacity. This upper-bound estimate reflects a technically possible but practically unattainable level of mobilisation, serving as a benchmark for understanding Spain's resource endowment.

CDR method	Conversion factor	CDR theoretical potential (2050)	Assumptions
Ecosystem management		**18.18**	
Afforestation/ reforestation	6.49 tCO_2/ ha/year	50.24	Using the 7.74 Mha classified as 'GLs shrub vegetation' according to the Spanish Forest Map cartography and the conversion factor obtained from the study *"Biomass and carbon fixation by young reforestation"* by INIA-CSIC, MITERD, and COITF[90].
Improved Forest Management (IFM)	2.52 tCO_2/ ha/year	31.52	Considering the hectares from Table 5, subtracting the Dehesa on forestland and the conversion factor obtained from a scientific article *Long term effect of different forest thinning intensity on carbon sequestration rates and potential uses in climate change mitigation actions*[91].
Agroforestry	2.74 tCO_2/ ha/year	3	Considering the total hectares of *dehesa* (1.09 Mha) to be restored and multiplying them by the conversion factor obtained from the seminar presented by the Spanish Society of Forest Sciences and the University Institute for Sustainable Forest Management, UVa INIA, with the collaboration of CSIC and the Regional Government of Extremadura[30].
Cropland management (Direct seeding and zero or conservation tilling)	3.12 tCO_2/ ha/year	25.79	Considering the hectares from Table 5 and the conversion factor obtained from the 4 per mil Initiative by MAPA[29].
Cropland management (vegetation cover)	5.65 tCO_2/ ha/year	20.62	Considering the hectares from Table 5 and the conversion factor obtained from the 4 per mil Initiative by MAPA[29].
Pasture management	1.10 tCO_2/ ha/year	5.81	Considering the hectares registered in the FEGA Ecoregimes[92] and a conversion factor obtained from the scientific article Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands[93].
Wetland and peatland restoration	2.7 t/ha/ year	1.3	If all 488.51 kha of degraded wetlands and peatlands were restored, 1.32Mt CO_2/year of carbon burial could be achieved.
Blue carbon	2.44 t/ha/ year	0.24	Estimations according to Red Eléctrica's report. 9.98 kha of *Posidonia oceanica* restored.
Biomass conversion		**18.18**	
BECCS (Combustion)	2.7 MWh/ tCO_2	8.6	Considering that 60% of the potential CO_2 storage is allocated to BECCS and the values for each use (Table 15).
BECCS (Anaerobic Digestion)	3.8 MWh/ tCO_2	4.9	Considering that 60% of the potential CO_2 storage is allocated to BECCS and the values for each use (Table 15).
Biochar	1.36 t/tCO_2	4.5	Considering that 50% of the biomass from thermochemical processes goes to pyrolysis, producing biochar.
Durable biobased products	0.9 tCO_2/m^3	0.18	Considering the structural wood (chapter 3.7.3) The estimated value for 2030 has also been used as a proxy for the year 2050.
Geochemical		**30.3**	
ERW (dolomite)	2.5 t/tCO_2	3	Considering all waste generation mineral is being used. Conservative assumptions on the conversion factor have been made (e.g. 2.5 t/tCO_2 instead of 1.8 t/tCO_2 mentioned in Bullock et al. 2023).
ERW (limestone)	2.5 t/tCO_2	18.7	
ERW (basalt)	4.3 t/tCO_2	0.1	
ERW (mafic rocks)	-	0.4	Assuming Spain opens mines for the extraction of mafic rocks reaching the scale of the existing basalt extraction
OAE (slags and limestone)	1.74 t/tCO_2	8.1	Using slags and part of the limestone.

continued>

CDR method	Conversion factor	CDR theoretical potential (2050)	Assumptions
Synthetic		**9**	
Electrochemical DACCS	0.78 MWh/ tCO_2	6.4	Considering that 6 TWh will be consumed by SDAC and LDAC, leaving 25 TWh for E-DAC and considering that 40% of the potential CO_2 storage is allocated to DACCS (Explained at the end of section 4.3 - CO_2 storage)
Low-temperature DACCS	1.5 MWh/ tCO_2	1.6	
High-temperature DACCS	1.75 MWh/ tCO_2	1	
DOCCS		0	DOCCS is theoretically possible, but considered not viable by 2050 as explained in Box 4 below.
Total		**196**	

Table 9. Estimated maximum theoretical CDR potential in Spain. Data in Mt CO_2.

Box 4. A note on Direct Ocean Carbon Capture (DOCCS)

Direct Ocean Carbon Capture is being developed with some projects operating in Europe. For this reason, it was not excluded from the assessment. However, when it comes to allocating limited resources, DOCCS currently combines a lower technology readiness level with higher energy requirements compared to other available methods (estimated at 2.15 MWh/tCO_2, with high uncertainty). As a result, DOCCS is assigned a lower priority to access the resources for now.

However, this should not be interpreted as lack of potential. DOCCS is only at the beginning of its technological maturation, a phase in which significant efficiency gains are expected. It also offers unique opportunities to leverage existing value chains and infrastructure - such as water treatment facilities - which are particularly relevant in a country like Spain.

Therefore, while DOCCS does not play a significant role in the scenarios built in 2026, it may represent a significant share of the "untapped" potential beyond what is deemed possible at this point in time."

4.2.1 Sensitivity analysis on the CDR theoretical potential without storage limit

Given that storage represents a significant constraint, a sensitivity analysis was conducted to assess Spain's potential CDR deployment assuming no storage capacity limitations. In this scenario, the contributions of BECCS and DACCS would depend solely on other resources, such as biomass and energy. Their contribution in this hypothetical case would rise significantly from 13.5 and 9 to **40** and **45 $MtCO_2$/year by 2050**, respectively (Table 10).

CDR method	$MtCO_2$/year	Notes
BECCS (Combustion)	25.5	Based on the biomass available for CDR illustrated in Figure 18.
BECCS (Anaerobic Digestion)	14.5	
Electrochemical DACCS	31.9	Assuming 6 TWh will be consumed by S-DAC and L-DAC, leaving 25 TWh for E-DAC.
Low-temperature DACCS	8	Considering the low-grade waste heat available.
High-temperature DACCS	5.1	Considering the high-grade waste heat available.
Total	**85**	

Table 10. CDR theoretical potentials assuming no CO_2 storage limit.

Taking these BECCS and DACCS figures into account, **the national potential for 2050 would be 258.5 $MtCO_2$/year**, instead of the 196 $MtCO_2$/year limited by CO_2 storage. This higher figure remains relevant because future advances in CO_2 transport and storage infrastructure, including international agreements for shared CO_2 storage and transport corridors and cross-border pipelines and shipping could unlock additional capacity. Such developments would enable Spain to leverage its biomass and renewable energy potential more fully, approaching this theoretical capacity.

4.3 Resource allocation in the theoretical CDR potential

Table 11 summarises the resource availability for estimating the theoretical potential of CDR in Spain by 2050 considering the scenarios of the resources and feedstocks described in Chapter 3.

Resource	2050	Assumptions
Energy (TWh)		
Renewable electricity	31	Assuming that only the electricity projected for export in the electricity 2050 scenarios in Figure 8 is available for CDR.
Waste heat (low grade)	12	Assuming the maximum range of the assessed scenarios (Table 3).
Waste heat (high grade)	9	
Water (bcm)		
Freshwater	106.7	Due to climate change, freshwater resources are expected to decrease.
Saltwater	1.5	To fight against water stress, a steady increase in desalination is expected.
Land (Mha)		
Annual arable land	8.27	Considering the land area available for CDR (Table 5).
Permanent arable land	3.65	
Forestland	14.92	
Grassland	11.77	
Peatlands (kha)	0.97	It is assumed that 2% of degraded peatland ecosystems would be restored by 2050, as per P4: Ambitious scenario in Table 6.
Peatlands (kha)	0.97	The loss of seagrass area is assumed to be partially recovered by 2050.
Biomass (MtDM)		
Forestry biomass	11.4	Considering the biomass available for CDR (Figure 18).
Agricultural/agro-industrial biomass	21.6	
Biogenic waste	16.5	
Mineral feedstocks (Mt)		
Limestone	55.6	Considering the upper bounds of the waste fractions estimations for 2050 (Table 7).
Dolomite	7.6	
Basalt	0.6	
Cement	6.3	
Steel slag	5.5	
CO_2 storage (Mt/year)		
Geologic reservoirs	22.4	Based on exponential curves created to estimate injection ratios according to estimated total theoretical capacity (Explained at the end of section 4.3 - CO_2 storage)
Mineralisation	1.5	Considering in-situ and ex-situ mineralisation.

Table 11. Summary of resource and feedstock availability for estimating the theoretical CDR potential in Spain.

2050	MtDM available for CDR	TWh	Conversion factor	Units	$MtCO_2$/ year	$MtCO_2$/ year (Storage limitation)	CDR method
Combustion	18	59.77	2.7	MWh/tCO_2	22.14	7.4	BECCS
Anaerobic digestion	19.3	55.1	3.8	MWh/tCO_2	14.5	4.9	BECCS
Thermochemical processes (Pyrolysis/ Gasification)[f]	12.2	50% Syngas	1.8	t/tCO_2	3.4	1.2	BECCS
		50% biochar	1,36	t/tCO_2	4.5	4.5	Biochar
TOTAL	**49.5**				**44.5**	**18**	

Table 12. Maximum theoretical resources and removal potential for biomass CDR methods.

Biomass

Given the diverse valorisation pathways for biomass, each feedstock was allocated to specific uses based on its physicochemical properties and typical applications in Spain, as per Table C.2 in Annex C. These allocations provide indicative estimates that may vary by region, technology, and market conditions.

For energy applications such as combustion and anaerobic digestion, each biomass category was converted into its corresponding energy potential. The conversion factors used for this assessment are presented in Table C.4 in Annex C, which provides the total theoretical amount of energy that could be obtained from the different biomass sources. This amount of energy makes it possible to estimate the theoretical CDR potential using additional conversion factors (see Table 12) which enable the transformation of energy values into the corresponding quantity of CO_2 that can be removed from the atmosphere.

By 2050, the share of biomass used for combustion is projected to decline as biomass is increasingly reserved for higher-value applications and energy demand shifts toward electrification. Biomass is expected to be increasingly allocated to advanced conversion pathways such as anaerobic digestion for biomethane production.

However, the amount of CO_2 that could be removed by these routes is limited by the geological capacity available for CO_2 storage. Considering the technical – low atmospheric CO_2 concentration – and energetic limitations of DACCS - particularly those associated with L-DAC - and the comparatively higher efficiency of BECCS, a distribution of 60% BECCS and 40% DACCS is deemed reasonable to ensure a more feasible and cost-effective carbon removal deployment.

CO_2 storage

To estimate the injection for the theoretical 2050 scenario, the analysis starts from the total theoretical capacity estimated for 2050 after applying the theoretical RAF (2081.6Mt) (Table 8). Exponential curves are then created beginning with an injection of 2 Mt in 2030 (a known figure from the TarraCO_2 project), assuming that the total theoretical capacity could be reached in 2060 and 2070. This assumption is made because it is reasonable to expect that not all the estimated capacity will be achieved by 2050, as not all storage sites will be operational and filled. These exponential curves (shown in Annex D) yield estimated injection values for 2050 of 59.81 Mt/year (2060 curve) and 21.72 Mt/year (2070 curve), so the mean value is taken, resulting in a total injection capacity for 2050 of 40.77 Mt/year (for both CCS and CDR).

f. From the available biomass, in addition to combustion and anaerobic digestion, a feedstock was allocated for thermochemical processes including pyrolysis and gasification, in order to take gasification into consideration since it may be a technology that could develop in the future and from which biogenic CO_2 can be obtained. However, as CO_2 capture for gasification is not yet as mature and its deployment is more uncertain, for practical purposes, as shown in general tables, the potential CO_2 it could generate has been accounted for together with BECCS from combustion, and only the biochar that would be produced through pyrolysis has been separated.

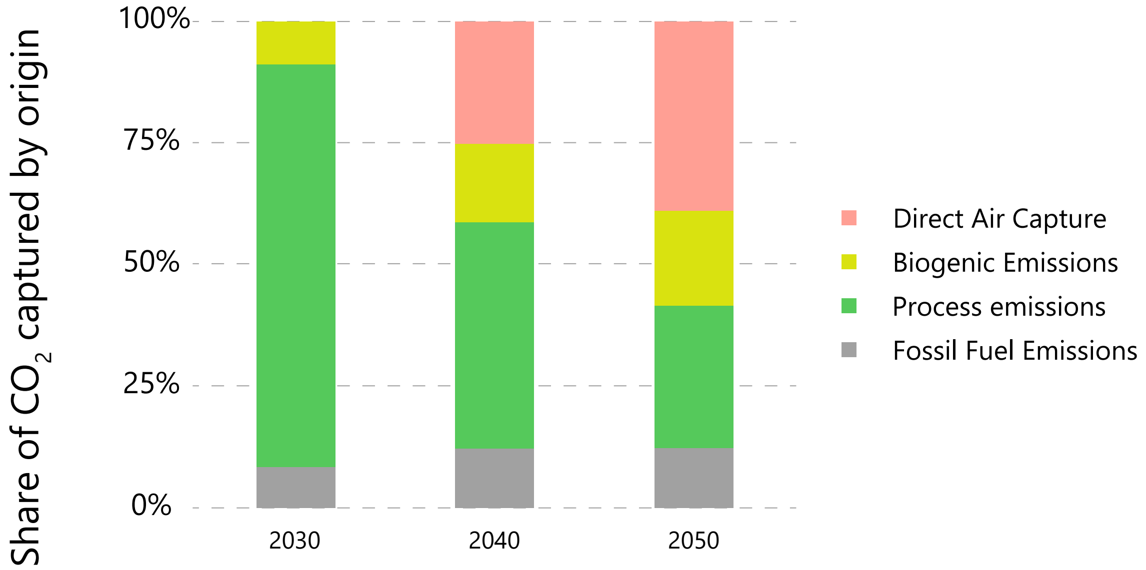
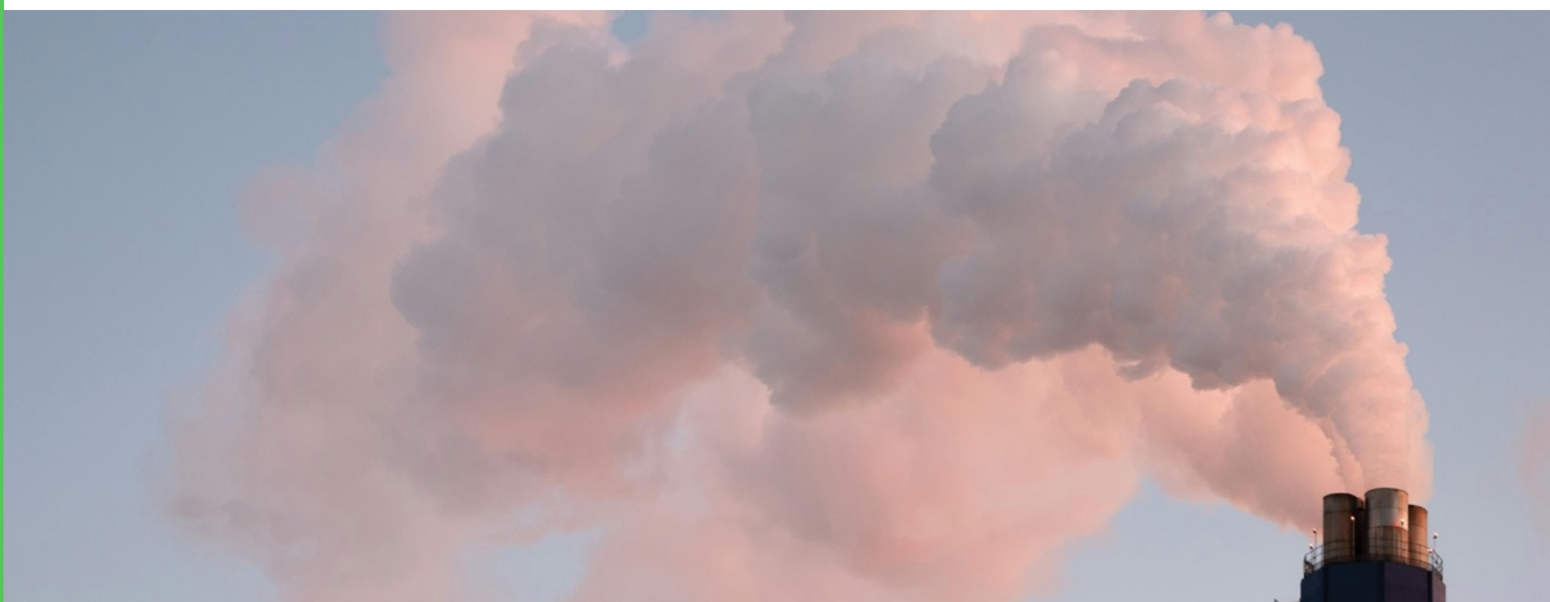


Figure 25. Projected distribution of CO_2 captured by origin according to the EU Communication on Carbon Management (COM) 2024[94].

Since Spain does not have a national carbon capture strategy, for this analysis it was decided to follow the allocation established by the EU in the *EU Communication on Carbon Management*. Following the CCS/CDR split established - 45% CCS and 55% CDR for 2050 - the distribution is applied, indicating that of the 40.77 Mt/year, approximately 22 Mt/year would be allocated to CDR.

Considering the nationally available biomass resources and the fact that the concentration of CO_2 in ambient air is substantially lower than in BECCS process streams, a distribution of 60% BECCS and 40% DACCS is assumed for the theoretical 2050 scenario. This allocation reflects both the expected technological progress of DACCS by mid-century and the anticipated cost reductions in both removal pathways.

It is worth noting that, although current studies are primarily focused on storage solutions for CO_2 captured through CCS methods, it is anticipated that in the future these facilities could also be used for CO_2 captured via CDR techniques.



5. Existing policy

Spain's climate strategy, as outlined in its updated **National Integrated Energy and Climate Plan** (NIEP), sets a course toward achieving net-zero GHG emissions by 2050. As of 2021, Spain's per capita CO_2 emissions stood at approximately 5 tons, accounting for 9% of the EU's total emissions. The primary sources include transport, industry, agriculture, and energy sectors, with fossil fuels (particularly oil and natural gas) contributing over 70% of the country's energy demand. While there was a downward trend in emissions from 2017 to 2020, recent years have seen a rebound, especially in the agriculture and transport sectors, indicating challenges in aligning with projected trajectories.

Table 13 summarises some of the Spanish strategies involved in its NECP. The country aims to reduce energy demand by increasing efficiency across sectors and to cover future electricity requirements by developing renewable electricity sectors at the expense of nuclear and coal. Furthermore, by 2050, it is expected that the country will achieve energy self-sufficiency and even turn into a major exporter of green hydrogen. The electrification of the road sector is another pillar and by 2040, a ban on the sales of internal combustion engine vehicles is expected to be imposed.

5.1 CDR within Spain's climate strategy

By 2030, Spain aims to reduce overall GHG emissions by 32% compared to 1990 levels, an increase from the previous target of 23%. Furthermore, **the country is committed to achieving carbon neutrality by 2050**, with a 90% reduction in emissions relative to 1990 levels which are estimated at a **maximum of 29 $MtCO_2$** per year. The remaining emissions are expected to be counterbalanced by natural sinks, which are expected to have a capture capacity of 37 $MtCO_2$ in 2050.

Spain's approach to CDR is currently limited and largely focused on ecosystem-based solutions such as afforestation and reforestation, wetland restoration, and sustainable agricultural practices.

Strategy area	Description	Resource allocation	Target to 2030	Target to 2050
Renewable electricity generation	Accelerate deployment of solar, wind, and hydroelectric power to decarbonise the electricity sector.	Significant investments in renewable infrastructure, supported by EU funds and national incentives.	81% of electricity from renewables	100% renewable electricity generation
Green hydrogen production	Position Spain as a European leader in green hydrogen, leveraging abundant renewable resources.	Government subsidies and foreign investments, including partnerships with international firms.	12 GW installed capacity	Major producer and exporter of green hydrogen
Electric vehicle adoption	Promote electrification of the transport sector to reduce emissions from road traffic.	Incentives for EV purchases, expansion of charging infrastructure, and regulatory measures.	5.5 million electric vehicles in operation	Ban on sales of internal combustion engine vehicles by 2040
Energy efficiency improvements	Enhance energy efficiency across sectors to lower overall energy demand.	Implementation of efficiency standards, retrofitting programs, and awareness campaigns.	Reduce primary energy consumption by 39.5%	Continued improvements leading to a highly energy-efficient economy
Phase-out of coal and Nuclear	Transition away from high-emission energy sources towards cleaner alternatives.	Managed phase-out plans with support for affected communities and workers.	Eliminate coal by 2025; decommission nuclear plants by 2035	Complete phase-out of fossil fuels; reliance on renewable energy sources
Reduction of Energy Import Dependency	Increase energy self-sufficiency through domestic renewable energy production.	Investments in local energy projects and diversification of energy sources.	Reduce dependency to 50%	Achieve energy independence through renewable energy production

Table 13. Description of strategies involved in the Spanish national energy and climate plan.

The national climate framework, primarily defined through the 2021–2030 **Integrated National Energy and Climate Plan (PNIEC)**, acknowledges the need for CO_2 removal to achieve net-zero emissions but places its emphasis almost exclusively on enhancing biological sinks, with little attention given to technological CDR options. At the same time, the Strategic Projects for Economic Recovery and Transformation (PERTE) for Industrial Decarbonisation, part of Spain's Recovery and Resilience Plan, mentions carbon removals in the context of applying BECCS[95,96,97,98,99], stating that this process could significantly reduce net emissions by counterbalancing released CO_2 emissions with those captured from the atmosphere during the growth phase of the biomass.

Spain is not currently positioned as a significant actor in the international carbon removal credits market, as its strategy prioritises domestic mitigation measures over the use of traded credits. While instruments such as the FES-CO_2 Carbon Fund support projects that may generate credits, international carbon markets do not play a central role in national climate planning.

At the policy level, investment in carbon capture and removal technologies remains very limited. Key planning instruments do not include technological CDR, and recent regulatory developments continue to focus on ecosystem based approaches. This position has been reinforced by policy and expert discussions, which highlight the low technological maturity and unresolved challenges of direct capture methods[88].

5.2 Legal frameworks relevant to CDR

Table 14 shows the key legal framework involved in the development of potential CDR methods in Spain. For weathering, the EU Soil Strategy and **Spain's Law 7/2022 on Waste and Contaminated Soils** apply primarily to pilot and R&D activities. More experimental options like OAE fall under broader environmental legislation, such as the **EU Marine Strategy Framework Directive** and **Spanish Coastal Law**, but remain largely unregulated and guided by the precautionary principle due to their potential ecological risks. Engineered solutions like DACCS are supported at the EU level through mechanisms such as the **Innovation Fund** and the **Net-Zero Industry Act** but face significant regulatory gaps in Spain.

Regarding storage, **Law 40/2010** of 29 December 2010 regulates the authorisation, operation, closure and associated liabilities of CO_2 storage in underground geological formations, both onshore and in the marine subsurface, provided that permanent confinement and environmental safety are ensured. Biochar is eligible for use as a soil improver under **Spanish RD 999/2017** and

CDR Method	Key normative (Spain/EU)	Description
Weathering	• EU Soil Strategy (2021) • Spanish Law 7/2022 (Waste and Contaminated Soils)	Still in pilot/R&D phase. Environmental and land-use impacts are under study[100,101].
Forestation/ Reforestation[102,103]	• EU Forest Strategy (2030) Spanish forestal plan • Spanish royal decree 214/2025	Forestry sink accounting is mandatory. Spain must report removals under the EU LULUCF regulation. Incentives available for reforestation projects[104,105,106].
Ocean Alkalinity Enhancement	• EU Marine Strategy Framework Directive • Spanish Coastal Law 22/1988	Considered a form of marine geoengineering, subject to precautionary principles. Still lacks specific legal framework in Spain[107,108].
Direct Air Capture (DACCS)	• EU Innovation Fund • Spanish CCUS Strategy (2023 draft)	Not explicitly included in the Spanish NECP[109,110].
Carbon Capture & Storage (CCS)	• EU Net-Zero Industry Act (2024) • Spanish Draft CCUS Strategy • Law 40/2010	Although the EU provides a framework, Spain has not defined specific CO_2 capture targets. No operational commercial CCS projects[109,11,112].
Biochar	• EU Circular Economy Action Plan • Spanish RD 999/2017 (fertilizers)	Recognised as a soil improver. Carbon accounting frameworks are under development. Voluntary carbon markets support their crediting[113,114].
Blue Carbon	• EU Biodiversity Strategy 2030 • Spanish Coastal Law 22/1988	Protected ecosystems. Restoration activities may be eligible for carbon credits; however, Spain lacks a clear carbon accounting framework for marine ecosystems[108,115].

Table 14. Key normative involved in the development of potential CDR methods in Spain.

supported by voluntary carbon markets, although standardised carbon accounting systems are still evolving. Lastly, blue carbon initiatives, while supported by EU and Spanish biodiversity and coastal legislation, are constrained by the absence of a defined carbon accounting methodology for marine ecosystems.

5.3 Support for R&D and Innovation

Spain's support for research and innovation related to CDR remains fragmented, although there are signs of increasing interest. Most government-backed R&D funding is channelled through national programs under the Ministry of Science and Innovation and the Centre for the Development of Industrial Technology (CDTI), which prioritise decarbonisation but do not yet explicitly target CDR as a strategic research area. Nevertheless, some technological CDR pathways, such as biochar, BECCS, and Direct Air Capture, have received indirect support through broader clean energy or circular economy initiatives. For example, the "Missions CDTI" program has funded several industrial decarbonization projects that could be extended to CDR, while Spain's involvement in EU-wide research initiatives under Horizon Europe has provided additional resources for pilot and demonstration activities related to CCUS[116].

There are also increasing efforts to integrate CDR into Spain's innovation ecosystem through collaboration between academia, public institutions, and industry. Several Spanish universities and research centres, including CIEMAT and the Basque Centre for Climate Change (BC3), have begun to explore the feasibility of geological storage, DAC, and biochar systems in national and regional contexts. The 2023 draft of the national CCUS strategy, while not yet formally approved, mentions the promotion of testbeds and living labs as a way to advance CDR deployment, with the potential use of public procurement for innovation (PPI) and contracts for difference (CfDs) as market enablers. However, the absence of dedicated CDR funding lines, technology-neutral tenders, or a structured innovation roadmap means that Spain still lags behind countries like the UK or Germany in fostering a dedicated CDR innovation ecosystem[117].

Future opportunities could be unlocked by integrating CDR into existing green industrial strategies, such as Spain's "PERTE for Renewable Energies, Renewable Hydrogen and Storage (ERHA)," which is backed by NextGenerationEU funding. While not explicitly designed for CDR, these programs create infrastructure and R&D environments that CDR actors could potentially leverage—especially for CO_2 transport, renewable energy integration, and biomass valorisation.

5.4 On the horizon

Spain's emerging policy landscape suggests that CDR could gain more traction in the coming years, though several institutional and technical gaps remain. A key milestone is the forthcoming approval of the National CCUS Strategy, which is expected to outline more concrete steps for the deployment of carbon capture, transport, and storage infrastructure -laying the groundwork for integrating both point-source CCS and CDR options such as BECCS and DACCS. This strategy, combined with evolving European regulations like the Net-Zero Industry Act (NZIA) and the proposed EU Carbon Removal Certification Framework (CRCF), could help harmonize incentives and standardise monitoring, reporting, and verification (MRV) frameworks across CDR methods.

Stakeholder engagement is also on the rise. Initiatives like the Enagás CO_2 Hubs and PCI projects (e.g., CO_2net2 Norte, MOSUSOL-NETCO$_2$) illustrate growing industry interest in building scalable infrastructure that could serve CDR applications. Similarly, Spain's increasing participation in international CDR networks and European climate dialogues (e.g., Mission Innovation's CDR Mission) positions the country to benefit from cross-border knowledge exchange, harmonised certification practices, and co-financing mechanisms[118]. However, challenges persist. The lack of a coordinated institutional champion for CDR, regulatory uncertainty regarding CO_2 storage, and low public awareness risk delaying deployment. A national roadmap that includes both nature-based and technological CDR pathways - aligned with Spain's net-zero goals - could help consolidate fragmented efforts and provide long-term visibility to innovators and investors alike. As such, the next few years will be critical for translating political will and technical feasibility into a cohesive policy framework for CDR deployment.

5.4.1 CDR players

In Spain, despite limited governmental support and the absence of a CDR strategy, a dynamic ecosystem is beginning to take shape. It brings together Research & Development institutions, associations, project developers, CO_2 management companies, and market brokers. The key actors currently driving this emerging landscape are presented in Figure 26.

5.5 Conclusions on existing policy

Spain's existing climate policy reflects strong ambition in decarbonisation, especially through the promotion of renewable energy, energy efficiency, and green hydrogen. However, its direct treatment of CDR remains limited, with most emphasis placed on enhancing natural sinks rather than developing technological CDR solutions. The updated NECP mentions the role of carbon sinks in meeting neutrality goals but fails to assign specific roles to CDR methods such as DACCS, BECCS, or OAE. As a result, there is a policy vacuum that hampers the integration of these emerging methods into long-term national planning. Without clear targets or incentive mechanisms, CDR development in Spain remains largely exploratory and lacks strategic direction.

Regulatory frameworks exhibit similar inconsistencies. While Spain has adopted EU-aligned legislation that supports renewable deployment and sustainable forestry, key enablers for CDR - such as legal authorisation of CO_2 storage and formal MRV frameworks - are still missing. Ocean-based and mineral CDR approaches, for instance, fall under broader environmental laws without specific guidelines, limiting both public and private sector engagement. Moreover, although R&D support exists through national innovation programs and EU funding, there is no designated funding line or institutional leadership for CDR. The fragmented legal and institutional landscape suggests that, to harness Spain's full CDR potential, a more coherent and proactive policy agenda must be established to acknowledge the urgency of integrating removals into the national decarbonisation strategy.

Figure 26. Current actors in the Spanish CDR ecosystem (2026)

6. Spain's social geography

This section aims to paint a picture of the social geography of the country, identifying the main enablers and limitations to the deployment of CDR. It is a combination of desk research and engagement exercises to capture the perceptions and aspirations of a diversity of relevant actors.

6.1 Overview

6.1.1 Economy

In recent years, Spain has moved from being one of the economies most affected by COVID-19 to becoming one of the main growth engines of the eurozone. In 2024, nominal GDP reached USD 1.73 trillion and real growth stood at 3.2%, with a 2.6% growth forecast for 2025. This performance is supported by domestic consumption, service exports, and a modernisation process based on digitalisation, renewable energy deployment, and labour-market reforms[119]. Key Macroeconomic Indicators include:

- **GDP and growth:** Economic activity is 5.7% above pre-pandemic levels (Q4-2019), with performance exceeding that of the eurozone.
- **Labour market:** The unemployment rate stood at 10.6% in Q4-2024, its lowest level since 2008, although it remains the highest in the European Union.
- **Productivity:** GDP per hour worked is around 5% above 2019 levels, although still below the EU average.
- **Well-being:** With an HDI of 0.918 (2023) and GDP per capita of USD 35,789 (2024), Spain is in the very high human development group.

Value added is concentrated in services (70% of GDP), followed by industry (18%) and agriculture (2.5%). Carbon intensity fell to 0.10 kg CO_2/USD in 2023, a 46% reduction since 2005, while total GHG emissions stood at 287.7 MtCO_2e. Offsetting these emissions through CDR would cost an estimated USD 14.4 billion (0.8% of GDP) at USD 50/tCO_2, rising to USD 28.8 billion (1.7%) at USD 100/tCO_2, USD 57.5 billion (3.3%) at USD 200/tCO_2, and up to USD 143.9 billion (8.3%) at USD 500/tCO_2.

At USD 100/tCO_2 – expected to be feasible for mature methods by 2030 – the fiscal impact would remain below 2% of GDP. Spain's strong economic base provides capacity to finance and scale CDR, though maintaining productivity growth, diversifying industry, and securing stable funding will be essential.

6.1.2 Political and public landscape

Spain's political landscape is characterised by a high degree of fragmentation, with a progressive coalition government that depends on support from regional parties and a strongly polarised opposition, particularly on climate-related issues. This situation affects both the stability of future electoral cycles and the public debate around climate neutrality and, increasingly, carbon dioxide removal (CDR). The current government is expected to remain in office until 2027, with key electoral milestones ahead, including the European elections in 2026 and regional and general elections in 2027.

Main political positions on climate policy:

- Progressive bloc (PSOE and Sumar): Supports the legally binding objective of climate neutrality by 2050 and promotes a combination of emissions reduction and CCS projects, including industrial hubs such as Bilbao.
- Partido Popular: Accepts the EU climate target but calls for "technological neutrality," advocating a stronger role for nuclear energy, more flexible interim targets, and a greater focus on industrial capture solutions.
- Vox: Rejects the scientific consensus on climate change, opposes green taxation, and calls for the repeal of existing climate legislation and low-emission zones.

Despite political polarisation, public support for climate action remains strong. According to Eurobarometer data, a large majority of citizens support climate neutrality by 2050 and consider climate change one of the main global challenges. However, this general consensus does not always translate into local acceptance when projects require visible infrastructure or land-use changes. Large-scale renewable energy projects, particularly wind and solar, have faced local opposition and legal challenges, notably in Galicia. While recent judicial rulings have enabled several projects to proceed, these cases highlight recurring tensions between national climate objectives and local concerns related to landscape, land use, and economic impacts.

At the same time, the discussion around CDR is gaining momentum:

- Royal Decree 214/2025 established a carbon footprint registry that allows the registration of carbon removal projects.
- The first continental plant producing carbonated aggregates, promoted by Petronor and O.C.O., is under development at the Port of Bilbao.

- Universities and NGOs continue to stress the primacy of emissions reduction and the need for robust permanence criteria, prompting the government to prepare integrity standards aligned with the EU Carbon Removal Certification Framework (CRCF).

Public acceptance of innovation tends to increase when benefits are clear and participation mechanisms are in place. Successful examples include the rapid deployment of digital infrastructure, such as 5G networks, and large energy-transition projects like the H2Med hydrogen corridor, which incorporated extensive public consultations.

Overall, Spain shows broad political and social support for climate neutrality by 2050, although disagreements persist regarding the pace and technological mix required. Translating this strategic support into local acceptance—through participatory planning, transparency, benefit-sharing mechanisms, and skills development—will be essential for the effective deployment of CDR solutions.

6.1.3 Relationship to ecology

Environmental awareness in Spain has intensified as the impacts of climate change have become more visible, particularly through droughts, wildfires, and extreme heatwaves. According to the 2025 Eurobarometer, Spain ranks among the EU countries with the highest levels of climate concern[120]. However, awareness of other environmental challenges, such as biodiversity, remains limited, despite broad social rejection of economic activities that damage protected areas. In this context, nature restoration is perceived as one of the most effective responses to environmental challenges[121].

Environmental concern has also translated into increasing social and legal mobilisation, alongside the implementation of EU-supported restoration and biodiversity projects. Nevertheless, significant challenges remain in converting this concern into tangible progress in mitigation, ecosystem restoration, and the effective deployment of carbon removal solutions.

6.1.4 Human Resources

Spain has a solid educational base, but scaling CDR faces two structural constraints: a declining pipeline of STEM graduates and rapidly growing demand for green jobs. Spain has experienced one of the largest drops in science and technology graduates in the EU, limiting the availability of specialised skills at a time when decarbonisation needs are accelerating.

This imbalance is already visible in the energy sector, where employment has grown rapidly, driven by renewable energy and emerging technologies such as green hydrogen[122]. While job creation is strong, the workforce remains geographically concentrated and shows persistent gender imbalances, with women underrepresented in technical and scientific roles.

In emerging areas such as hydrogen and CCS, targeted training initiatives are being developed, combining digital tools and practical experience. However, the supply of highly specialised profiles—particularly in reservoir modelling, process engineering, and applied research—remains insufficient. Spain operates in a competitive international labour market, with higher salaries abroad attracting experienced professionals, although some return with accumulated expertise[123].

Overall, Spain's existing industrial base and infrastructure provide a strong foundation for integrating CDR, but successful deployment will depend on expanding technical training, retaining specialised talent, and aligning education, industry, and policy to meet future skills demand.

6.1.5 Industrial integration

Spain has a sufficiently broad and diversified industrial base to integrate multiple CDR pathways by leveraging existing infrastructure and value chains, particularly in construction, the water cycle, mining, and the bioeconomy.

The starting point is construction: the building and civil works market generated nearly USD 180.8 billion in 2024, slightly over 5% of national GDP, and continues to grow, driven by energy rehabilitation and green infrastructure, according to estimates based on information published by "Cifras INE-Construcción" and Eurostat's construction investment series[124]. This scale makes the cement sector —whose plants still manufacture and consume around 30 Mt annually— a decisive player: in 2024 alone, it exported 4.82 Mt of clinker, while its installed capacity enables CO_2 to be absorbed in kilns or mineralised in by-products, according to data from Oficemen, the industry association that reports monthly to Eurostat. The potential for capture and use is already materialising in the Petronor – O.C.O Technology agreement, which will build the first continental factory for carbon-negative aggregate at the Port of Bilbao; it will use CO_2 from the refinery and local demolition dust, an abundant flow considering the country generates around 33 Mt of construction and demolition waste annually, according to the European Commission.

Spain operates more than 760 desalination plants with a combined capacity of around 5 million m^3 per day, placing it among the world's top five producers of desalinated water, according to MITECO data[125] The hypersaline brines discharged from these facilities are an ideal substrate for emerging alkalinisation and mineral capture methods. The second piece is the water cycle. The PERTE for the Digitalisation of the Water Cycle mobilises €3.06 billion in public and private investment and launches specific calls for proposals for the urban cycle and irrigation. In August 2024, €300 million was awarded in the second call for proposals for the urban cycle; in 2023, €200 million in aid was granted, and in December 2024, the third call for proposals was opened. This momentum provides an ideal foundation for pilot carbonation projects in brines, without the need to start from scratch in terms of infrastructure[126].

Spain's strategic metals are concentrated in the Iberian Pyrite Belt and across Extremadura. Even so, the sector's production value slipped to €3.571 billion in 2023, driven mainly by price volatility. According to MITECO, legacy mining residues - over 200 Mt of tailings and waste rock—constitute a sizeable secondary feedstock for carbon mineralisation[127]. In parallel, lithium projects in Cáceres and tin–tungsten assets in Galicia are well positioned to dovetail with prospective CO_2 transport corridors to the Cantabrian coast.

The fourth pillar is the bioeconomy. Agricultural value added reached €37.625 billion in 2024, equivalent to 2.5% of GDP; this implies a stable base of residual biomass - prunings, olive pomace, cereal straw— that could feed pyrolysis or BECCS plants. Euthenia Energy's new plant in Córdoba, capable of processing 35,000 t/year and producing 8,000 t of certified biochar, demonstrates that soil sequestration is technically viable and is beginning to generate carbon credits for the voluntary market. Additionally, initiatives like Carbonfields in Soria and olive-grove recarbonisation pilots are testing end-to-end, fully domestic value chains.

Table 15 shows data on size, share of national production, and subcategories useful for CDR, based on data published by MITECO.

In conclusion, the existing facilities and logistical chains - cement kilns, demolition networks, desalination plants, tailings ponds, and a biomass-intensive agri-industry - provide Spain with fertile ground to integrate CDR methods without the need to build all the infrastructure from the ground up. The major challenge will be to coordinate certification standards, access to finance, and technical training so that these production circuits capture and lock in carbon at the pace required to achieve climate neutrality by 2050.

6.1.6 Cultural, aesthetic, religious and ethical considerations

Spain approaches any deployment of climate infrastructure within a cultural framework that is highly sensitive to the landscape and historical heritage: with 50 UNESCO World Heritage Sites, any project must comply with the requirements of Law 16/1985 on Historical Heritage, which obliges developers to demonstrate aesthetic and heritage

Sector	Economic size (€)	Domestic production share	CDR-relevant sub-categories
Construction, cement and construction and demolition waste	€95.1 bn GVA in 2023 (5.4 % of GDP)	94% of demand met by 12 cement plants; 1.37 Mt imported vs 22.2 Mt produced; 4.8 Mt clinker exported (2024)	Concrete dust & fines (~33 Mt/yr), slags, fly ash
Agriculture & biomass	€37.8 bn agricultural income in 2024 (2.5 % of GDP)	≈ 90 % of staple foods produced domestically; net exporter of fruit, vegetables & olive oil	Vine/olive prunings (~20 Mt/yr), cereal straw (~8 Mt/yr), pig slurry (~55 Mm^3/yr)
Mining & aggregates	€3.57 bn production value in 2023 (−9 % YoY)	> 65 % self-sufficiency in aggregates & ornamental stone; > 50 % imported for Cu & Li	Tailings & waste rock (~200 Mt accumulated); quarry dust
Water cycle & desalination	≈ €2.6 bn/yr in treatment services; ≈ 950 plants, ~5 Mm^3/day capacity	100% of desalinated water produced domestically; Spanish companies export operation and maintenance services.	Hypersaline brines (> 60 g/L); reverse osmosis sludge and reject streams.

Table 15. Sector national production.

compatibility from the project's early stages. This requirement is reinforced by mandatory public consultations in environmental procedures, fostering a participatory culture that can either delay - or legitimise - investments depending on the quality of the initial dialogue.

From an ethical and religious perspective, the largely Catholic —though not highly practising (Almost 53% of Spaniards identify as Catholic, but only 17% are practising) — population has embraced the encyclical *Laudato Si* as a moral reference: parishes and Church-linked NGOs support restoration initiatives and natural carbon sinks, turning "integral ecology" into an argument in favour of carbon removal.

In conclusion, Spanish culture favours climate action as long as projects respect heritage, involve communities, and are presented as an intergenerational ethical duty. However, as previously mentioned, certain CDR or renewable energy projects may still face public rejection, highlighting the need to improve environmental education across society. Although the public is generally aware that such actions are necessary, there tends to be a negative perception when these projects affect nearby areas, replace traditional activities, or lead to changes in land use.

6.2 Stakeholder interviews

This section summarises the findings from the analysis of 23 interviews conducted with key stakeholders in the field of climate policy and CDR in Spain. These interviews were carried out in July and August 2025, for a total of 23 hours. The interviewees represent a diverse sample including public administrations, research centres, private companies, industrial associations, and civil society organisations (Table 16). All of them are typically involved in the formulation or implementation of policies related to energy, the environment, CCS, and other related areas.

The aim of this analysis is to provide a consolidated view on three fundamental aspects: stakeholders' knowledge and opinions on the country's current climate policy, their level of familiarity with different CDR methods, and their perceptions regarding the deployment of these solutions as a tool to tackle climate change. The information gathered makes it possible to identify points of consensus, divergences, and critical factors influencing the adoption of CDR methods in the Spanish context.

6.2.1 Awareness and views on Spain's existing climate policy

Stakeholders broadly agree that Spain has an ambitious regulatory framework aligned with EU climate goals. However, they caution that implementation, especially of CDR methods, remains slow and uneven. Public entities such as OECC, IHOBE, and regional administrations point to existing tools and plans, but acknowledge that deployment is largely confined to nature-based approaches like afforestation/reforestation (ARR), and improved forest management (IFM). Despite signs of political will, recurring barriers include administrative complexity, poor coordination across government levels, and a lack of targeted incentives.

Academy and research centres share the view that Spain is active in mitigation, but CDR is underdeveloped. Researchers point to the lack of a clear roadmap, insufficient investment in R&D, and weak links between science and policy, in addition to the overreliance on natural sinks without exploring other options.

Private companies value the national targets but consider them unrealistic unless supported by incentives and regulatory measures. While some, such as Sylvestris or Fundación Repsol, promote ARR, and IFM projects, most private companies — including the aforementioned ones - perceive the economic risks and uncertainties associated with more complex methods.

Stakeholder type	Stakeholders interviewed
Public entities and administrations	OECC, IHOBE, Consorcio de Aguas, Govern Balear, Principado de Asturias
Academy and research centres	Universidad de Oviedo, IGME, CSIC, TECNALIA
Private companies	Minersa, Fundación Repsol, ENAGAS, Sylvestris, Balearia
Business / industrial associations	SIDEREX, Aclima, FEAF, CEBEK, ADEGI, Basque Energy Cluster
NGOs and civil society	COPADE, Greenpeace, ECODES

Table 16. The 23 interviewed stakeholders.

Industrial associations stress that current regulations are disconnected from industrial realities, creating investment insecurity. Finally, NGOs emphasise the need for a more coherent vision with social and environmental challenges, calling for policies that integrate climate justice and citizen participation.

6.2.2 Awareness and knowledge of CDR and its methods

Knowledge of CDR is uneven. **Public administrations and NGOs** are familiar with nature-based solutions but lack in-depth understanding of industrial options, which are met with some scepticism.

Academy and research centres, on the other hand, possess high technical expertise and clearly distinguish the potential and limitations of each method. They identify soil-related solutions, peatland and coastal wetland restoration, and biochar as promising, while methods such as DACCS or OAE are seen as too costly and uncertain in their impacts.

Private companies show fragmented knowledge: those engaged in forestry projects dominate the field, while the rest have limited awareness of emerging methods, reducing their willingness to invest. Industrial associations' knowledge is mostly confined to simple, nature-based methods, while other approaches are perceived as experimental.

Across all stakeholder groups, there is a general concern about the lack of clear information and robust monitoring systems, which hinders the establishment of trust.

6.2.3 Views on the Deployment of CDR in Spain

Regarding the deployment of CDR, all groups agree that Spain has potential, but the current reality is limited. The main obstacle identified is the absence of a specific regulatory framework that goes beyond ARR, and IFM. Additional challenges include high costs, lack of sustainable economic models, limited social awareness, and, in many cases, local opposition to geological storage projects. Logistical and territorial issues are also mentioned, such as biomass availability, wildfire risks, and difficulties in finding suitable sites.

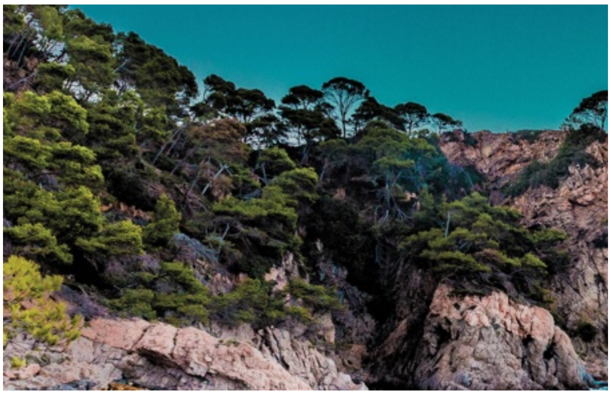
Despite these challenges, several factors could facilitate greater deployment. Stakeholders highlight the need for sustained political momentum, supported by European and national funding, fiscal incentives, and a long-term strategy. Public-private collaboration is valued as a key driver, and there is strong emphasis on the importance of environmental education and communication to generate social acceptance.

There is consensus that nature-based solutions - such as ARR, IFM, peatland and coastal wetland restoration, and soil carbon storage - are the most viable in the short term, as they offer environmental and social co-benefits. One NGO, for their part, do not regard CDR as a solution and supports nature-based approaches solely for the additional benefits they provide; moreover, it is highly critical of industrial CDR methods and calls for greater climate ambition and social action to meet the 2050 targets. The other stakeholder groups, meanwhile, view industrial methods - despite the scepticism they arouse - as necessary in the medium and long term, provided that research, regulation and proof of their feasibility continue to advance.

A summary of the results from the stakeholder interviews is provided in Table 17.

6.2.4 Conclusions on the stakeholder interviews

The analysis shows that Spain has an ambitious climate framework but suffers from limited and uneven implementation. There is consensus that nature-based solutions are the most viable in the short term, though they require proper management and monitoring. Industrial methods, while promising, raise concerns about their cost and lack of development, so their adoption will depend on advances in R&D and regulation. The main barriers identified are the absence of clear incentives, lack of administrative coordination, and low public awareness. However, there are opportunities if policies are strengthened, public-private collaboration is promoted, and European funds are harnessed. To move forward, Spain needs a national strategy that combines natural and industrial solutions, supported by science, investment, and the participation of all stakeholders.



Stakeholder type	Awareness of general climate policy in the country	Level of commit-ment to decarboni-sation	Awareness of specific CDR policies	Knowledge of CDR	Short-term outlook	Key drivers or stakeholders thought to be most appropriate to drive CDR in Spain
Public entities and administrations	High	Medium-high	Medium-high	Medium-high	Moderately optimistic	**Key drivers:** environmental education, public administrations, Technological improvement and monetary incentives. **Stakeholders:** Central government, regional governments (Autonomous Communities), provincial councils and municipalities, and Industrialists and agricultural producers.
Academy and research centres	High	Medium-high	Medium	Medium-high	Moderately pessimistic	**Key drivers:** political interest, knowledge, and financial investment. **Stakeholders:** Central government, and regional governments (Autonomous Communities).
Business/ industry associations	Medium-high	Medium	Medium-low	Medium-low	Moderate	**Key drivers:** Public-private collaboration, public policies through investments, and the economy. **Stakeholders:** Central government, public administrations and private sector, MITECO, regional governments (Autonomous Communities), Government and opposition parties.
Private companies	Medium-high	Medium-high	Medium	Medium-low	Moderately optimistic	**Key drivers:** creation of a semi-mandatory market. **Stakeholders:** Central Government, research centres, public administrations, industrial sector, OECC, Autonomous Communities.
NGOs	High	High	High	High	Moderately optimistic	**Key drivers:** environmental education, high-level political spheres **Stakeholders:** Society, municipalities, the State, industries

Table 17. Summary and assessments obtained from interviews with experts.

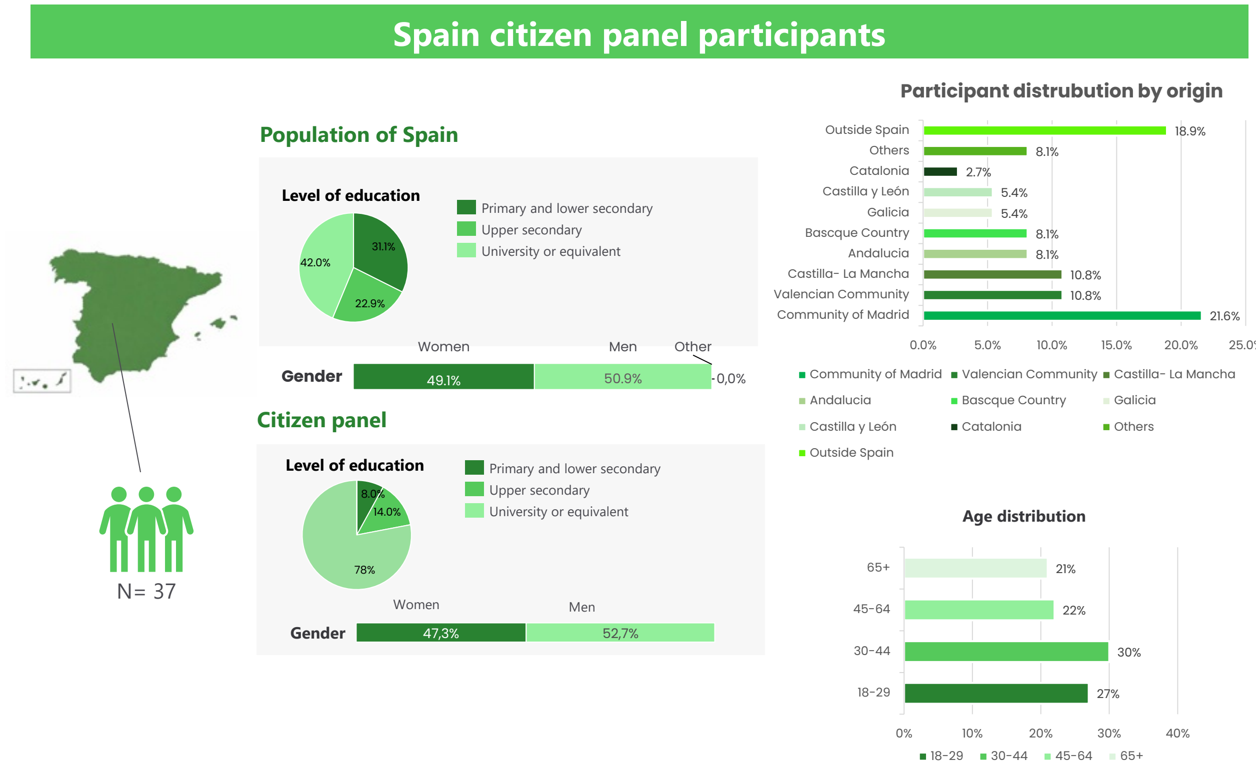


Figure 27. Composition of citizen panel by age, education level, and origin.

6.3 Citizen panel

As part of the social geography assessment, a citizen panel was held in September 2025 in Madrid to explore the general public's perception of technological and natural solutions that promote CDR. The panel was attended by 37 people, representing a wide diversity in terms of age, gender, academic background, professional experience and geographical origin. The gender split was almost equal, the age distribution was broadly balanced, and education levels were overall high, as seen in Figure 27. Moreover, participants came from across Spain and abroad.

Before the panel, participants received one-page summaries of each CDR method, covering advantages, drawbacks, and broader context. This material was shared in writing and via a webinar, available live and on demand. A pre-panel survey captured initial views, with results shown in the graphs below.
The three-hour session combined small-group discussions with a plenary. Citizens were encouraged to share perspectives openly and request further information. Dialogue followed a method-by-method structure - starting with perceived benefits and concerns, concluding with a synthesis of preferred CDR approaches for Spain.

6.3.1 Awareness and views of stakeholders on the existing climate policy of the country

Citizen panel participants stressed the importance of decoupling climate action - which over 60% rated as important or very important, with no opposing views - from political cycles and shifting electoral priorities. They believe that addressing climate change requires a unified, global effort in which all citizens play an active role. While national goals are well-founded and progress is underway, participants called for increased investment and public awareness to accelerate momentum. Recognising the scale of the challenge, they emphasised the need for comprehensive policies and tools at both national and international levels.

6.3.2 Awareness/knowledge of CDR and the different methods

Citizen panel participants were unaware of the existence of these methods and the fact that they were being promoted as mechanisms for CDR. They highlighted the difficulty of understanding each of the methods analysed, as well as their associated implications and challenges, acknowledging that very specific technical knowledge is required to grasp them fully. Given this lack of understanding, they expressed concern about the uncertainty of

PREFERRED CDR METHODS

- Afforestation, reforestation
- Improved forest management
- Soil carbon sequestration
- Biochar
- Peatland and coastal wetland restoration
- Durable bio-based products

AVERAGE ACCEPTANCE

- Enhanced rock weathering (ERW)
- Carbon mineralisation
- Bioenergy with carbon capture and storage (BECCS)
- Biomass sinking and burial

LEAST PREFERRED

- Direct air capture and storage (DACCS)
- Direct ocean capture and storage (DOCCS)
- Ocean alkalinity enhancement

Figure 28. Classification of CDR methods according to the opinion of citizen panel participants.

the potential impacts, the need for clarity and public awareness, and the importance of not losing sight of the real objective: changing consumption habits and lifestyles to prevent and reduce emissions.

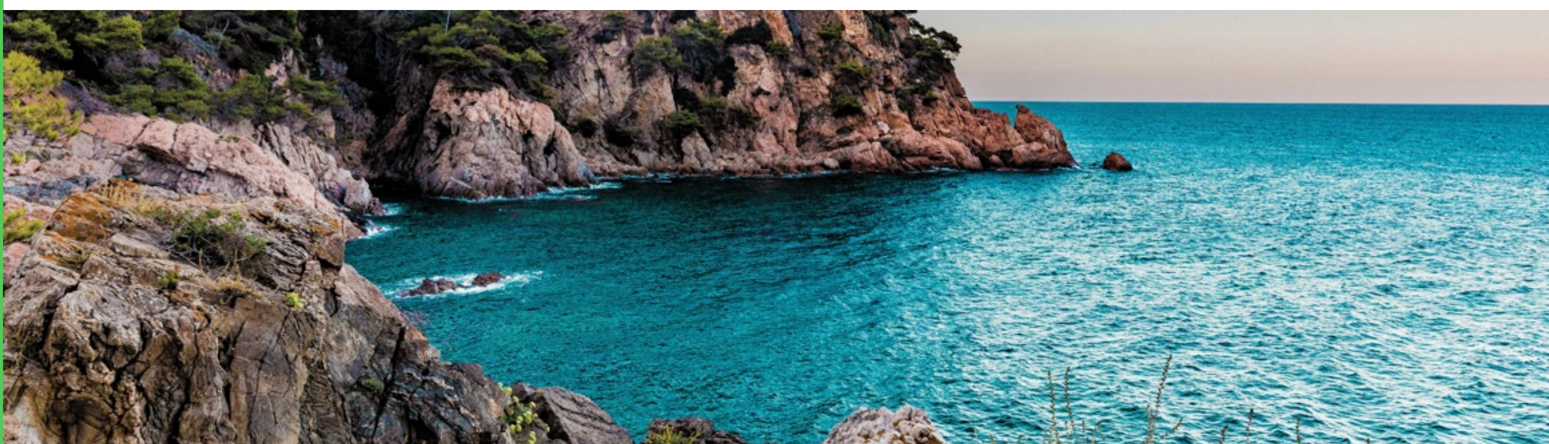
The information provided changed at least slightly, the perception of most (66%) of the participants. A very small minority (9%) maintained their position, and almost a quarter of them (24%) did not answer. It is important to note that all of them showed concern for climate change (considering it by unanimity, a global threat).

Nature-based CDR methods - such as afforestation/reforestation, peatland restoration, biochar, and carbon farming - received the highest levels of acceptance. In contrast, DACCS and OAE were strongly rejected, with participants citing concerns over the high energy demand and CO_2 storage requirements of the former, and the potential ecological risks of the latter.

6.3.3 Views on the deployment of CDR in the country and its use to fight climate change

Citizen panel participants viewed nature-based carbon removal methods as the most acceptable and promising, largely due to their perceived realism and added co-benefits such as biodiversity conservation, soil improvement, and water management. ERW and biochar were also seen as having potential, particularly as complementary solutions within a broader portfolio. In contrast, other CDR approaches were considered less viable at this stage, primarily due to technological immaturity, high costs, and potential negative side effects (Figure 28). Nonetheless, some participants expressed optimism that DACCS and BECCS could gain momentum if new CCU pathways beyond storage emerge, technological readiness advances, and costs decline.

Participants emphasised the importance of acknowledging who has been primarily responsible for the problem, alongside the need for a fair and equitable distribution of costs among countries. Once again, there was a strong call for education and increased public awareness. Responsibility, they stressed, should not rest solely with public institutions - it must also be shared by schools, businesses, families, and other societal actors. Overall, citizens expressed a positive attitude toward implementing CDR methods to mitigate climate change, with 18 participants strongly in favour, 9 supportive, and only one somewhat opposed.



7. Spain's realistic potential to deploy CDR (Can do)

Building on the resource overview in Chapter 3 and the theoretical CDR potential outlined in Chapter 4, this chapter revises assumptions around resource availability and selected CDR methods to incorporate stakeholder perspectives, public sentiment, and the legal and socio-economic considerations discussed in chapters 5 and 6. Based on this integrated analysis, we estimate the realistic potential – defined as the volumes of CDR that can be deployed with high confidence in the foreseeable future. Within this framework, multiple scenarios remain possible, largely shaped by Spain's level of ambition. This chapter explores those pathways in detail.

7.1 Methodology for the realistic CDR potential

The realistic CDR potential in Spain was calculated using the same methodology as the theoretical potential in Chapter 4, but with added constraints such as regulatory, economic, and social factors. The assessment of social acceptance is based on the views gathered through the stakeholder interviews and the citizen panel described in Chapter 6. Unlike the theoretical assessment in Chapter 4, which assumes full resource allocation to CDR, the realistic estimate is more conservative as it accounts for competing demands and constraints, resulting in lower projected CDR volumes. These more cautious estimates are based on the following considerations:

- **Techno-economic feasibility:** in addition to physical constraints, resource use was evaluated in terms of what is reasonably feasible from a techno-economic perspective - particularly for resources that are contested among multiple CDR methods. However, macroeconomic variables such as GDP growth, cost levels, interest rates, and existing financial support mechanisms were not included as dynamic inputs.
- **Technological deployment**: the pace and scope of technology rollout were adjusted to reflect realistic expectations. For example, adoption rates for methods such as BECCS and DACCS were estimated for 2030 and 2050 based on plausible deployment trajectories.
- **Legislative constraints:** legal limitations were incorporated where they clearly and significantly limit the availability of certain resources. The most notable example is *Ley 40/2010 de almacenamiento geológico de* CO_2, which imposes strict permitting, liability, and site-selection requirements for geological storage, and the limited scope of the national *Registro de proyectos de absorción de* CO_2 *under Real Decreto 214/2025*, which currently recognises only a narrow set of land-based absorption projects.
- **Social acceptance** was assessed through public support, as determined by input from stakeholder interviews and the citizen panel. Social acceptance was treated as a limiting factor for certain methods, particularly DOCCS and OAE, and the distribution between BECCS and DACCS. OAE was excluded on this basis, while DOCCS was excluded because of both lack of social acceptance and high costs that would make it unfeasible in a realistic scenario (see Box 4). Regarding the social acceptance of DACCS, the main constraint was the public's limited familiarity with the technology. Consequently, DACCS has not been penalised in the assessment on grounds of social acceptance. The allocation between BECCS and DACCS was made considering other key constraints, including the cost differences between both approaches, the greater technical difficulty of capturing CO_2 directly from ambient air - given its very low concentration - and the availability of biomass resources required for BECCS deployment (see section 7.4.6).

As with the theoretical potential, a bottom-up approach was applied to most CDR methods.

7.2 Realistic CDR potential scenarios

To assess Spain's realistic carbon dioxide removal potential, this study outlines three scenarios for 2050:

- **Reference scenario** aligned with climate targets currently in law;
- **Conservative scenario** reflecting the status quo with no additional effort made to deploy CDR and assuming a limited deployment of CDR methods due to barriers such as insufficient investment, lack of a clear regulatory framework, severe climate impacts, low public acceptance, limited public–private collaboration, and an increase in forest fires, among other factors;
- **Ambitious scenario** assuming additional measures allowing to go beyond (or faster) existing climate targets, with strong support for CDR methods and less adverse climate effects.

Compared with Spain's projected residual emissions in 2050 (29 $MtCO_2$, LTS[1]), the CDR potential is

~17 $MtCO_2$/year by 2050 in the **Conservative** scenario, **~52 $MtCO_2$/year** in the **Reference**, and **~68 $MtCO_2$/year** in the **Ambitious**, excluding natural sinks. Additional Reference scenarios for 2030 and 2040 illustrate a plausible ramp-up of CDR deployment over time and are illustrated in Table A.1 in Annex A, which also summarises the key assumptions.

Across all three scenarios, **ecosystem management methods** emerge as the primary CDR methods (Figure 29). This is largely due to resource availability, broad social acceptance, and strong public recognition. While methods such as DACCS and BECCS may offer greater potential, their deployment is constrained by limited CO_2 storage capacity.

In all scenarios, peatland restoration, coastal revegetation, durable biobased products, and enhanced rock weathering are considered, but their potential is very negligible. *Posidonia* restoration emerges as the most feasible marine CDR method after accounting for the results on citizens' and stakeholders' preferences, but its potential is minimal. Ocean alkalinity enhancement (OAE) is deployed to a minimal extent only in the Ambitious scenario due to social rejection. Peatland restoration offers high carbon burial potential, but current efforts remain minimal relative to the surface available, despite the PNIEC targets. Direct Ocean Carbon Capture remains economically unviable (see Box 4), even when considering potential deployment by 2050. High-temperature DACCS does not have any potential because high-grade heat is assumed to be allocated completely to industrial usage.

7.2.1. Reference scenario

In the Reference scenario, the annual CDR potential for Spain is **~52 $MtCO_2$ per year in 2050**. Adding the capacity of projected natural sink (14 $MtCO_2$), Spain could remove **~66 $MtCO_2$** annually in 2050. In the Reference scenario, Spain's target of absorbing 29 $MtCO_2$ by 2050, which is required to achieve climate neutrality once emissions have been reduced by 90%, is achieved with removals from ecosystem management methods, which account for ~34 $MtCO_2$/year by 2050.

The main CDR methods in the 2050 Reference scenario are **cropland management**, removing **12 $MtCO_2$/year** and **improved forest management** (**10 $MtCO_2$/year**). In this scenario, even though improved forest management (IFM) projects are not currently recorded in Spain, and the Spanish Climate

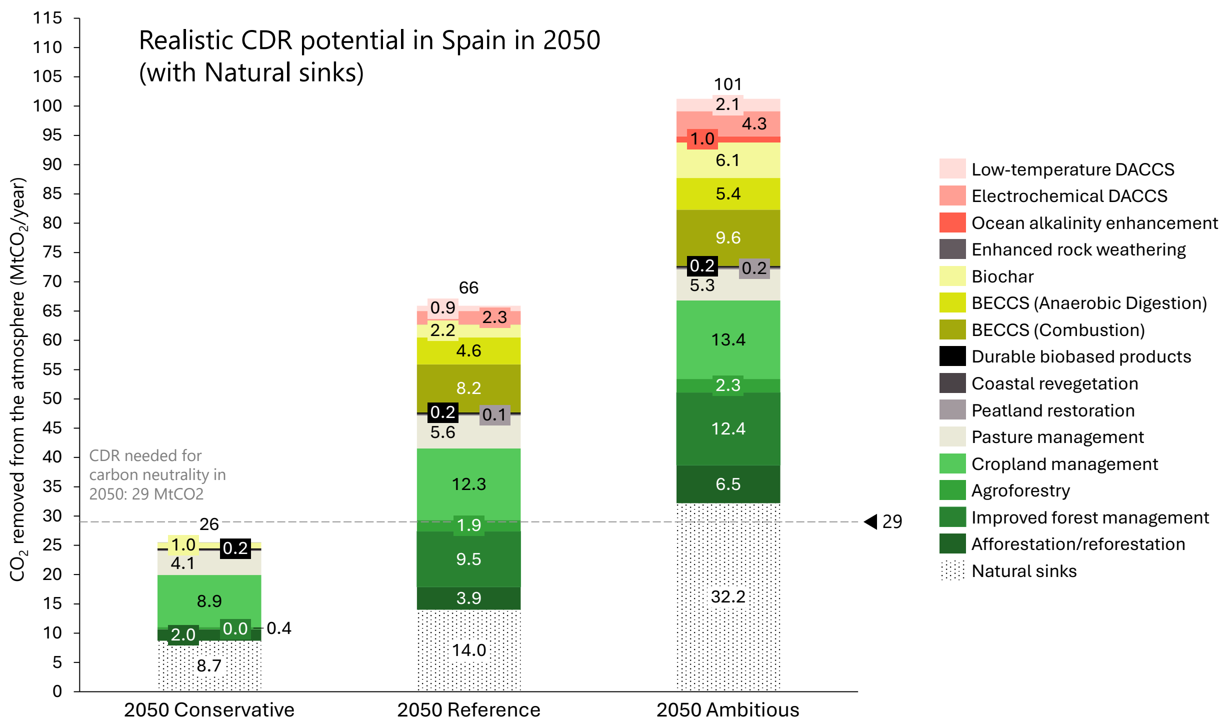


Figure 29. Spain's realistic CDR potential in 2050 across the Conservative, Reference and Ambitious scenarios compared to the 2050 expected residual emissions (29 $MtCO_2$).

Box 5. Forest sink (excluding additional CDR)

As a current reference, unchanged forest land has sequestered an average of 29.15 $MtCO_2e$/year (incl. CDR) over the past two decades (National GHG Inventory[128]). In the Conservative scenario, carbon removal practices are meant to prevent further deterioration, but would not increase sink capacity beyond current levels. Furthermore, current figures refer to the entire forest sink, which includes both CDR measures and natural ecosystem uptake. In this report, we exclude sequestration from CDR methods from the natural sink.

By 2050, total uptake by natural sinks and CDR is projected to be 37 $MtCO_2$, while the natural sink (excluding CDR) is projected to be **14 $MtCO_2e$/year** in the Reference scenario, based on a conversion factor of 1.88 tCO_2/ha/year for unmanaged forest stands according to data from the National GHG Inventory. The Conservative scenario estimates **~8.7 $MtCO_2e$/year**, both below today's levels due to climate change. MITECO's Long-Term Decarbonisation Strategy[1] notes that *"signals of saturation are already being observed, leading to a decline in total absorption."*

Improved management could slow degradation but is unlikely to boost carbon sequestration beyond current levels given climate pressures. In the Ambitious scenario, the sink (excluding CDR) remains at the same level as last year, **32.16 $MtCO_2e$/year**, representing a situation in which climate impacts are less severe and the forest sink area increases.

Change Office's voluntary carbon market standard does not yet recognise IFM as an eligible project type, it was assumed that IFM would experience a similar growth to sustainable forest management certification (e.g. PEFC and FSC).

Other important methods of note are **BECCS with combustion (8 $MtCO_2$)**, **pasture management (6 $MtCO_2$/year)**, and **BECCS with anaerobic digestion (5 $MtCO_2$)**. Afforestation/reforestation is estimated to remove **~4 $MtCO_2$** per year based on the assumption that the target of af-/reforesting 0.6 Mha from the Spanish Forest Strategy[24] is fully met (0.6 Mha reforested by 2050). **Agroforestry, biochar, and electrochemical DACCS** contribute about **2 $MtCO_2$/year** each, while **low temperature DACCS** contribute the least with less than 1 $MtCO_2$/year.

7.2.2 Conservative scenario

As shown in Figure 29, the annual CDR potential for Spain in the Conservative scenario is **~17 $MtCO_2$/year** in 2050. Adding the capacity of projected natural sink (8.7 $MtCO_2$), Spain could remove **~26 $MtCO_2$ in 2050**. The Conservative scenario does not remove the expected residual emissions in 2050 even when considering natural sinks.

The main CDR methods in this scenario are **cropland management**, which removes **9 $MtCO_2$/year**, followed by **pasture management** (**4 $MtCO_2$/year**). **Afforestation/reforestation** is estimated to remove **2 $MtCO_2$** per year under the assumption that only half of the target from the Spanish Forestry Strategy horizon 2050[24] - which sets a target of reforesting 0.6 Mha between now and 2050 - is achieved, reflecting challenges such as wildfires, policy setbacks, limited funding, and climate impacts. **Biochar** also contribute to the potential in the Conservative scenario, with 1 $MtCO_2$/year. IFM is assumed to be zero in the Conservative scenario due to unsuccessful forest management practices. Similarly, agroforestry is assumed at a minimal level not meeting the PNIEC restoration objective (see section 7.3.3). BECCS and DACCS are excluded from this scenario due to a lack of CO_2 storage.

7.2.3 Ambitious scenario

In the **Ambitious** Scenario, the annual CDR potential for Spain is **~69 $MtCO_2$ in 2050**. Combined with the projected natural sink capacity of 32 $MtCO_2$, total removals could approach **~101 $MtCO_2$/year**, far exceeding the 29 $MtCO_2$ residual emissions that need to be counterbalanced to achieve net-zero.

In this scenario, the main CDR methods are **cropland management** (13 $MtCO_2$/year) and **improved forest management** (IFM) (12 $MtCO_2$/year), followed by **BECCS with combustion** (10 $MtCO_2$). IFM is assumed to be highly successful, growing 30% more than in the Reference scenario.

Afforestation/reforestation is estimated to remove **7 $MtCO_2$/year** under the assumption that the target of the Spanish Forestry strategy is overachieved by 0.4 Mha driven by improved practices and reduced climate pressures – for a total of 1 Mha reforested. **Pasture management** contributes **5 $MtCO_2$/year**, less than the Reference scenario, since it is assumed that in the Ambitious scenario highly successful reforestation reduces a significant portion (9%) of grassland, cutting the pasture management area accordingly. In the Ambitious scenario, **biochar (6 $MtCO_2$/year)** and **BECCS with anaerobic digestion (5 $MtCO_2$)** provide major contributions to carbon removal. **Electrochemical DACCS** adds a further **4 $MtCO_2$/year**, while **low-temperature DACCS** removes **2 $MtCO_2$** per year. **Agroforestry** contributes an additional 2 $MtCO_2$/year. In this scenario, **ocean alkalinity enhancement** is deployed using carbonate feedstocks and contributes **1 $MtCO_2$** of removal per year.

7.3 Resource allocation

As outlined in Chapter 3, Spain has substantial resources available for CDR. This section details how these resources are allocated across different CDR methods. Table 18 presents the share of resources used in each realistic scenario, while a summary of total resource availability is provided in the Annex B.

7.3.1 Allocation of renewable electricity

In terms of availability, the electricity available for CDR in the realistic scenarios is assumed to correspond to the export-bound electricity described in the four scenarios in section 3.1.1 (Figure 8). In the Conservative scenario, it corresponds to the renewable fraction of the forecasted electricity exports in *Scenario E1: Stable electricity, stable mix* (22 TWh). The Ambitious scenario assumes the same amount as the theoretical scenario (31 TWh) based on all the estimated electricity exports of *Scenario E4: high electricity, renewable mix*. The Reference scenario is instead assumed to have 26.5 TWh available for CDR - the midpoint of the Ambitious and Conservative estimations.

In the Reference and Ambitious scenarios, renewable electricity is allocated to electrochemical and low-temperature DACCS. Around 8% of renewable electricity is used in the Reference scenario, while the Ambitious scenario uses 14%. None is used in the Conservative scenario as DACCS is not deployed.

7.3.2 Allocation of waste heat

Only low-grade heat is assumed to be available for CDR, as high-grade heat is fully directed to industry, leaving none for CDR applications. Waste heat availability for CDR in the realistic scenarios is estimated to be 6 TWh in the Conservative scenario, in alignment with the *T2: Stable thermal demand* scenario; 12 TWh in the Ambitious scenario as per *T1: Stable thermal demand* scenario (Figure 10); and 9 TWh in the Reference scenario, which corresponds to the midpoint value.

In the Reference and Ambitious scenarios, waste heat is allocated to BECCS (combustion) and low-temperature DACCS, using almost all availability. None is allocated in the Conservative scenario as DACCS and BECCS are not deployed.

7.3.3 Allocation of land

Overall, in relation to land, the realistic scenarios are based on Spain's Long-Term Decarbonisation Strategy developed by MITECO[41], which targets 37 Mt CO_2e/year absorbed from natural sinks by 2050 to achieve climate neutrality. In the Reference scenario, this target is achieved, in the Conservative scenario the target is not met and climate change impacts are greater. The Ambitious scenario instead represents an ideal situation in which forest policy is a political priority, backed by substantial investment, strong public approval of reforestation and forest conservation, effective forest management and limited effects of climate change.

Resources	Reference 2030	Reference 2040	Conservative 2050	Reference 2050	Ambitious 2050
Energy (TWh)					
Electrical energy	0% of 15.5	2% of 19	0% of 22	8% of 26.5	14% of 31
Thermal energy	0% of 11.82	34% of 10.42	0% of 6.03	99% of 9.04	100% of 12.05
Water (bcm)					
Fresh water	0.018% of 108.85 (0.02)	0.028% of 108.5 (0.03)	0.019% of 105.2 (0.02)	0.037% of 107.6 (0.04)	0.045% of 110 (0.05)
Salt water	0	0.6	2.28	2.98	3.68
Land (Mha)					
Annual arable land	12.45% of 8.19 (1.02)	13% of 8.17 (1.06)	9.9% of 7.98 (0.79)	13.24% of 8.16 (1.08)	14.26 % of 8.28 (1.18)
Permanent arable land	41.14% of 3.62 (1.49)	42.74% of 3.6 (1.54)	32.64% of 3.5 (1.14)	43.74% of 3.59 (1.57)	46.85% of 3.65 (1.71)
Forestland	0	12.4% of 18.2 (2.26)	14.33% of 18.42 (2.64)	20.5% of 18.39 (3.77)	26.2% of 18.69 (4.90)
Grassland	63.36% of 8.55 (5.42)	69.26% of 8.5 (5.89)	52% of 7.94 (4.13)	75.77% of 8.45 (6.40)	74.79% of 8.88 (6.64)
Peatlands (kha)	0	0.73% of 60 (0.44)	1.21% of 60 (0.73)	1.5% of 60 (0.91)	1.6% of 60 (0.97)
Underwater surfaces suitable for seagrass restoration (kha)	0	5% of 49.6 (2.48)	20% of 49.6 (9.92)	25% of 49.6 (12.4)	26.6% of 49.6 (13.19)
Biomass (MtDM)					
Biomass for BECCS - combustion	38.84% of 33.7 (13.1)	55.29% of 28.6 (15.8)	54.90% of 24 (13.2)	63.21% of 24 (15.2)	91.50% of 24 (22)
Biomass for BECCS - anaerobic digestion	37.07% of 10.3 (3.8)	55.94% of 14.3 (8)	54.22% of 19.4 (10.5)	59.39 % of 19.4 (11.5)	90.37% of 19.4 (17.5)
Biomass for biochar	50% of 3 (1.5)	50% of 5.4 (2.7)	25% of 6.1 (1.5)	50% of 6.1 (3)	100% of 6.1 (6.1)
Minerals					
Limestone	0% of 2.052	0% of 2.131	0% of 2.211	0% of 3.88	21% of 5.556
Dolomite	0% of 0.29	0% of 0.389	0% of 0.523	0% of 0.639	0% of 0.760
Basalt	100% of 0.008	100% of 0.01	100% of 0.011	100% of 0.03	100% of 0.06
Cement kiln dust (CKD)	28% of 0.318	24% of 0.378	21% of 0.439	22% of 0.536	24% of 0.63
Steel slag	0% of 0.189	0% of 0.196	0% of 0.204	0% of 0.377	100% of 0.55
CO_2 storage					
Geologic reservoirs	0	100% of 5.6	0	100% of 15.95	100% of 21.45
Mineralisation	100% of 0.03	100% of 0.03	100% of 0.03	100% of 0.04	100% of 0.05

*Table 18. Share of available resources used for CDR methods in each scenario. The percentages refer to the share of resource used for CDR in the realistic scenarios **out of the total resource available for CDR** (as shown in Annex B). No percentage is given for saltwater given the huge amounts available. For BECCS combustion, the biomass available for CDR includes all biomass available for combustion plus the half of the biomass allotted to thermochemical processes, as per Table C.3.*

Grassland allocated to reforestation

In the theoretical potential, the entire grassland area where pasture management would not be carried out and that was not classified as *Dehesa* was used for reforestation. However, in the realistic scenarios, additional constraints are considered, such as the lack of investment, the shortage of labour, and the absence of a clear and collaborative policy framework.

Dehesa (grassland and forestland) allocated to agroforestry

As mentioned in Box 1, the *dehesa* forms the foundation of Spanish agroforestry, with 1.09 Mha theoretically available for restoration. The realistic potentials of agroforestry are based on the restoration potential of the *Dehesa* and align with the PNIEC target of regenerating 28 kha/year[129]. In the Conservative scenario, only 20% of this target is achieved (5.6 kha/year), while in the Ambitious scenario the PNIEC objective is exceeded by 20%, reaching 33 kha/year. In addition to the *dehesa*, other agroforestry systems - such as annual crops combined with trees - could in principle be considered. However, in Spain these silvoarable systems are practically non-existent and lack both significant implementation and consistent national-scale data. For this reason, they were not included in the assessment, which focuses on the *dehesa* as the only widely established and mappable agroforestry system in the country.

Grassland allocated to pasture management

Grassland area available for pasture management in the realistic scenarios is **5.28 Mha**. This is the result of deducting the 1.09 Mha of *Dehesa* from the total national grassland area of 6.37 Mha, as registered by the CAP subsidies in the 2025 *Report on Climate- and Environment-Friendly Schemes ("Eco-schemes")*[92]. This definition is consistent, as without practices such as direct mowing or extensive grazing, these grassland areas would not be maintained. Therefore, CO_2 removals from pasture management will be proportional to the projected grassland area in 2030, 2040, and the three scenarios for 2050, but they will also depend on social factors. According to the trends described in Chapter 3, the pasture management removals would vary as follows in 2050:

- Conservative scenario: As reforestation targets are not met, grassland area expands by 1.64%. However, rural abandonment, the decline in livestock farming, and farmers' unfavourable perception of CDR methods mean that this new area, together with 30% of existing grasslands, remains unmanaged. As a result, the area available for grassland management is reduced by 30%, reflecting the decline in extensive grazing.
- Realistic scenario: with reforestation targets met for 2050, grassland declines by 3.29%, reducing pasture management by the same proportion.
- Ambitious scenario: reforestation is highly successful and a significant portion of grassland is lost, resulting in a 9% reduction. The area for pasture management decreases by –9%.

Arable land allocated to cropland management

For cropland management, the Ministry of Agriculture, Fisheries and Food (MAPA), through the Crop Area and Yield Surveys (ESYRCE)[26], highlights two key practices in Spain: direct seeding in annual crops (13.7% of agricultural area, 0.9 Mha), and vegetative cover in woody crops (25%, 1.4 Mha). Over the past decade, these techniques have grown by 65% and 15%, respectively. Their promotion is part of the "4 per 1000 Initiative: soil organic carbon as a tool for climate change mitigation and adaptation in Spain"[29], which establishes the conversion factors (tCO_2/ha/year) used to estimate CO_2 absorption. While Chapter 4 presented unrestricted values, real-world limitations – such as incompatibility with organic farming, landowner mistrust, rural abandonment, and lack of economic incentives – must be considered. Accordingly, three scenarios are proposed to reflect varying levels of implementation.

The 2050 Reference scenario assumes an increase in the absorptions from these techniques, consistent with the National Energy and Climate Plan (PNIEC), which does not provide quantitative targets but encourages their wider adoption in its "Measure 1.25 Agricultural Sinks"[129]. In this scenario, carbon storage practices would absorb 12.25 $MtCO_2e$/year, 10% above current levels, reaching 2.65 Mha of farmland where these RDC methods are applied, reflecting a balanced adoption of these techniques by farmers. This reflects a cautious, indicative uplift aligned with the PNIEC's qualitative guidance.

The 2050 Conservative scenario represents an unfavourable situation in which farmers do not support the initiative, and the effects of climate change severely impact agricultural land, leading to abandonment and thus a decrease in surface area where these CDR methods are practised. Carbon storage practices would absorb 8.91 $MtCO_2e$/year in the Conservative scenario, 20% less than the current absorption falling to 1.93 Mha where they would be applied.

The 2050 Ambitious scenario represents a highly favourable situation in which these methods are widely adopted by farmers, leading to a 20% increase over current adoption levels, reaching 2.90 Mha. Carbon storage practices would absorb 13.36 $MtCO_2e$/year in the Ambitious scenario.

7.3.4 Allocation of biomass

Biomass allocated to BECCS

In both the **2050 Conservative scenario** and **2030 Reference scenario**, the absence of geological CO_2 storage rules out any BECCS deployment. Yet biomass would still be available. By 2030, even with limited capture technology in biomass plants and constrained infrastructure, roughly 40% of the 2030 theoretical BECCS potential could be realised if storage was available – equivalent to about 16.9 Mt of biomass allocated to BECCS by 2030. Looking ahead to 2050 under the Conservative scenario, around 23.7 MtDM of biomass could be available for BECCS, highlighting the scale of opportunity that hinges entirely on securing storage options.

In the **2040 Reference scenario**, rising bioenergy use and expanding BECCS capacity could unlock around 60% of the theoretical BECCS potential, supported by 23.8 MtDM of available biomass (15.8 Mt for combustion and 8 Mt for anaerobic digestion). However, as in other cases, this potential would be drastically reduced by storage limitations. By 2040, BECCS would take 90% of the storage available for CDR, resulting in a BECCS 2040 removal potential capped at 5 $MtCO_2$/year.

In the **2050 Reference scenario**, a moderate development of biogas use is expected, which is intended to be promoted, along with the implementation of carbon capture methods in some biogas plants in the country, as well as in biomass combustion industries that have nearby infrastructure for CO_2 transport and storage. It is assumed that 26.7 MtDM of biomass would be available for BECCS (15.2 Mt for combustion and 11.5 Mt for anaerobic digestion).

As previously shown in Table 12, around 44.5 Mt CO_2 could be captured with BECCS in 2050. However, part of the captured CO_2 will be allocated for utilisation, mainly biogenic CO_2 for the production of e-fuels. A major pathway for utilising captured CO_2 is the production of synthetic fuels, an area governed by stringent EU rules. Under the ReFuelEU Aviation initiative, airlines are required to gradually increase the share of sustainable aviation fuels (SAF) in their blends, moving from 2% in 2025 to 34% in 2040 and reaching 70% by 2050. Within this mandate, a specific quota applies to renewable fuels of non-biological origin (RFNBOs), which must rise from 1.2% in 2030 to 35% in 2050. At present, RFNBOs can be produced using either biogenic or fossil-based CO_2, but

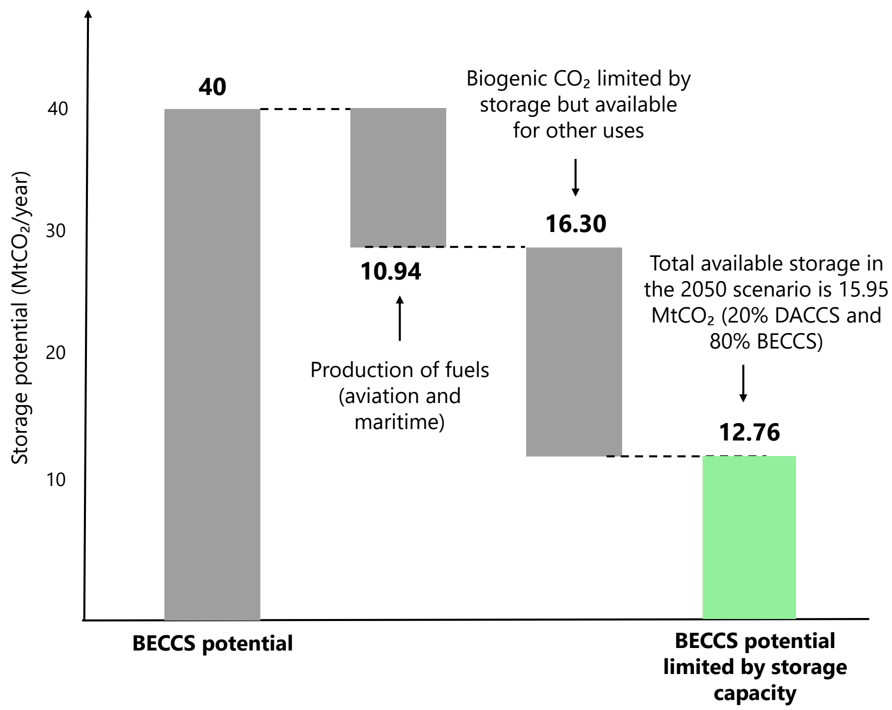


Figure 30. BECCS potential limited by storage capacity in the 2050 Reference scenario.

Regulation (EU) 2023/1185 establishes that - starting in 2040, or 2035 in the case of the power sector - only CO_2 of biogenic origin will qualify these fuels as low-carbon. This regulatory shift effectively secures a baseline level of demand for biogenic CO_2[130]. This requires approximately 2.59 Mt of e-SAF per year and 9.84 Mt of biogenic CO_2 annually in Spain.

For sea transport 0.36 Mtoe are estimated to be needed[131], equivalent to approximately 0.8 Mt e-methanol. According to IRENA 2021[132], to produce 1 tonne of methanol, about 1.38 t of CO_2 are needed, so around 1.1 Mt CO_2 would be used. On top of this, BEECS has the storage limitation. For the Reference scenario It is estimated that 80% of the total storage available for CDR (15.95 Mt CO_2) would be allocated to BECCS (see section 7.3.6). This translates into an availability of **12.8 Mt CO_2** for BECCS in 2050.

In the **2050 Ambitious scenario**, a greater development of available geological storage and transport infrastructure is assumed. Moreover, given the EU roadmap, an increase in biomass use for energy is expected, which will contribute to a boost in BECCS deployment. Also in the Ambitious scenario, although there is sufficient biomass resource for significant BECCS potential, around 39.5 MtDM (22 Mt for combustion and 17.5 Mt for anaerobic digestion, the amount of CO_2 from BECCS remains considerably limited due to the scarce availability of CO_2 storage at national level. For the Ambitious scenarios 70% of the total storage available for CDR (22.45 Mt CO_2) would be allocated to BECCS. That would mean about 15 Mt CO_2 for BECCS in 2050.

Biomass allocated to biochar

Based on the theoretical biomass availability assessed in 2050 for biochar, which is 6.1 Mt/year (half of the biomass considered for thermochemical processes), the volumes of biomass available for CDR in the realistic scenarios considered the following factors that may limit the deployment of biochar:

1. Technical constraints around logistical costs for biomass collection and transport and on quality controls (MRV) to ensure long-term stability

2. Economic constraints such as high production costs (equipment, energy), weak domestic market, with demand mainly in agriculture, competition for biomass from other sectors (biogas, pellets).

   Other costs associated with biochar application, e.g. purification before field deployment, have not been fully factored into volume estimates. According to industry sources, these costs could amount to around $200 per tonne of CO_2 removed to achieve economic viability.

3. Regulatory constraints such as lack of financial incentives or subsidies, and the complexity and costs of certification (e.g., European Biochar Certificate).

4. Knowledge & Awareness Gaps among farmers and stakeholders, and the few large-scale demonstration projects that are still insufficient to build confidence.

Considering these constraints, the **Reference scenario** assumes 50% of the theoretical maximum volume (3 Mt/year), which could enable the sequestration of roughly 2.2 $MtCO_2$/year by 2050. The same logic has been applied to 2030 and 2040, assuming 50% of the theoretical value for each year, which results in 1.5 Mt/year and 2.7 Mt/year of biomass available for biochar, respectively. For the **Ambitious scenario**, 100% of the theoretical maximum (6.1 Mt/year) is assumed, while the **Conservative scenari**o assumes 25% of the maximum (1.5 Mt/year) is realistically available.

Biomass allocated to durable bio-based products

Structural timber, specifically cross laminated timber (CLT), has been considered as the representative durable bio based product. For 2030, it is estimated that approximately 183,750 m^3 of CLT will be used. Given that producing 1 m^3 of CLT requires about 2.5 m^3 of roundwood[133], this corresponds to an allocation of roughly 459,375 m^3 of wood biomass for durable bio based products. For 2040 and 2050, the same values have been applied, as the available data and projections are insufficient to provide robust estimates for these years.

7.3.5 Allocation of minerals

In the realistic scenarios, we assume that no other mineral feedstocks would be available for CDR apart from the waste fractions from the mineral feedstock production estimated in Table 7. This is to acknowledge the low awareness and support that currently exists in Spain, most probably preventing the country from opening new mines for CDR applications. Accordingly, the theoretical potential of mafic bedrocks identified in Chapter 3 is discarded here.

Furthermore, for the Conservative scenario, it was assumed a low waste generation rate, reaching a feedstock availability of **0.11 Mt** of basalt, **22.11 Mt** limestone, **5.23 Mt** dolomite, **4.39 Mt** cement, and **2.04 Mt** of steel slags by 2050. For the Ambitious scenario, it was assumed a high waste rate generation, leading to a feedstock availability of **0.56 Mt** of basalt, **38.83 Mt** limestone, **6.39 Mt** dolomite, **5.36 Mt** cement, and **3.77 Mt** of steel slags. Finally, the Reference scenario assumed a midpoint between the Conservative and Ambitious scenarios, leading to a feedstock availability of **0.23 Mt** basalt **30.49 Mt** limestone, **5.81 Mt** dolomite, **4.88 Mt** cement, and **2.91 Mt** of steel slags by 2050. For all three scenarios, it was assumed that up to 10% of that waste dust can be effectively collected, considering that only a limited fraction of fine particles can be recovered from open quarry operations due to dispersion, humidity, and equipment limitations. Cement kiln dust and steel slag were allocated to mineralisation (CO_2 storage), while limestone and dolomite were not considered as realistic ERW feedstocks due to the limited and inconclusive literature on the carbon removal effectiveness of carbonate minerals. As a result, the estimated realistic CDR potential of ERW is assumed to come from basalt and it reaches less than 0.01 Mt CO_2 by 2050. OAE is assumed to be deployed only in the Ambitious scenario using carbonate rocks like limestone or dolomite.

7.3.6 Allocation of CO_2 storage

A bottom-up analysis has been conducted to define more realistic injection rates in the realistic scenarios, considering the current development status of storage projects.

In the realistic 2030 scenarios, **no geological storage capacity is assumed available for CDR**. This is due to the TarraCO$_2$-Storage project still undergoing technical validation[62]. If any storage capacity was available by then, it is reasonable to assume that it would be allocated primarily to the management of CO_2 from industrial sources (i.e. CCS) rather than allocated to CDR. This assumption is consistent with the Carbon Management Communication[94], which states that by 2030 nearly all captured CO_2 will originate from process and fossil fuel–related emissions.

For the estimation of the annual injection capacity in the following scenarios, the distribution between CCS technologies and CDR methods established by the EU is applied, as shown in Figure 31, ensuring methodological consistency and alignment with European climate objectives.

Under this criterion, in the **2040 Reference scenario**, it is assumed that TarraCO$_2$ storage will inject CO_2 from both fossil and biogenic sources, in line with the expected evolution of the capture mix. By that time, the Maestrazgo and Murcia storage sites are also expected to be operational, each offering annual injection capacities comparable to TarraCO$_2$. Additionally, a set of high-risk storage facilities, primarily deep saline aquifers and other geological structures, will complement these sites. It is projected that two to four of these additional facilities will be in operation by 2040, with injection levels similar to or exceeding those of TarraCO$_2$. Based on this set of assumptions, the **total CO_2 injection attributed to CDR methods in 2040 amounts to 5.6 MtCO$_2$/year**. This result reflects the expected pace of project maturity in Spain, conditioned by the infrastructure currently available, the priority given to the deployment of CCS-focused facilities, and the inherent uncertainty associated with the development of new storage sites, including social considerations linked to their implementation.

Three cases are considered for the realistic scenario in 2050: a conservative scenario, a reference scenario, and an ambitious scenario.

- **Conservative scenario 2050: It is assumed that no geological storage capacity will be available for CDR methods**, and that the limited capacity in operation will be exclusively allocated to CCS. This assumption is consistent with the European Carbon Management Strategy, which establishes that geological storage should prioritize emissions from hard-to-abate industrial sectors, such as cement, steel, or chemical production. Although CDR is recognized as a key tool to achieve climate neutrality, current European storage projects, and therefore those in Spain, continue to focus primarily on CCS due to the high volume of industrial emissions and the urgency of their reduction.
- **Reference scenario 2050**: In the 2050 horizon, the TarraCO$_2$ storage site is expected to increase its annual injection capacity, incorporating a growing proportion of CO_2 originating from CDR methods. Regarding the Maestrazgo and Murcia storage sites, and given that the total estimated capacity of Maestrazgo is approximately twice that of TarraCO$_2$ while Murcia's is nearly three times higher, both sites are assigned an annual injection rate proportional to that projected for TarraCO$_2$, in line with their greater geological potential and anticipated level of development. Additionally, between four and six further storage sites are expected to have entered operation by 2050, all of them with an annual injection capacity exceeding that initially attributed to TarraCO$_2$. The advancement of these sites is

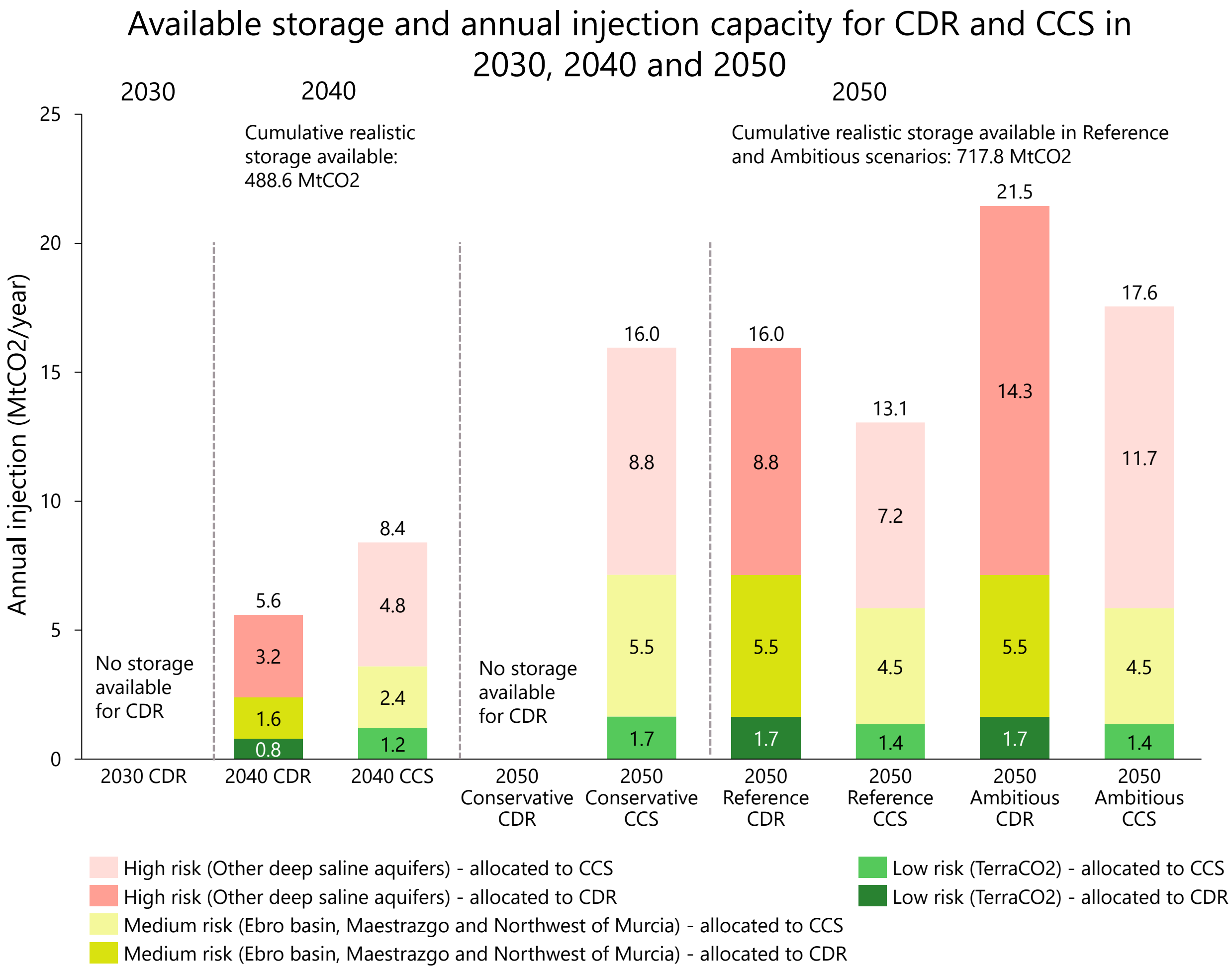


Figure 31. Estimated annual injection capacity (MtCO₂/year) for CDR and CCS in the different realistic scenarios across 2030, 2040, and 2050. Cumulative realistic storage capacity is with RAF applied (see section 3.7)

supported by the expansion of CO_2 transport infrastructure, the progressive improvement of social acceptance, and the increasing priority that the European Union assigns to CDR technologies within its long-term climate objectives. Under this set of assumptions, the **total injection capacity allocated to CDR in the 2050 Reference scenario amounts to 15.95 MtCO₂/year**.

- **Ambitious scenario 2050**: In this scenario the assumptions regarding TarraCO₂, Maestrazgo and Murcia remain identical to those of the reference scenario. However, it is assumed that between seven and ten additional storage sites have become operational by that year, reflecting a significantly more accelerated deployment of the national storage system. As a result of these assumptions, the **total injection allocated to CDR in the ambitious 2050 scenario amounts to 21.45 MtCO₂/year**. This scenario entails substantial progress in transport and storage infrastructure, greater regional integration within the European carbon management framework, and a sustained increase in social and political acceptance of CDR technologies.

As explained above, a bottom-up approach has been adopted to define the realistic scenarios due to the absence of a specific national strategy on geological CO_2 storage and the current priority given to CCS over CDR. Furthermore, given that Spain does not yet have any operational bilateral agreements for cross-border CO_2 storage —apart from its participation in the PYCASSO project (France)[134] - the **analysis has been limited to national injection capacity**.[g] Nevertheless, it is expected that in the

g. CO_2 exports are therefore not considered in any of the storage scenarios presented in this report.

future Spain will establish agreements with Portugal and France, as well as interconnections with existing and planned storage facilities in the North Sea. As European and national policies continue to evolve, a progressive increase in the use of biogenic CO_2 is also anticipated, driven by regulations promoting biocarbon routes. Consequently, across all projected scenarios, the total volume of CO_2 allocated to geological injection could increase substantially.

Accounting for the limited geological storage capacity: BECCS and DACCS

Geological CO_2 storage constitutes a critical and potentially limiting factor for the deployment of carbon removal solutions based on BECCS and DACCS.

In the **2030 Reference scenario and the 2050 Conservative scenario for 2050, the participation of these methods is not considered**, as the available storage capacity would be fully allocated to carbon capture and storage (CCS) projects associated with industrial sources. This exclusion reflects the need to prioritize the decarbonization of the most emission-intensive industrial sectors, in line with the European Carbon Management Strategy[94], which recognizes CCS as an essential tool for reducing emissions in hard-to-abate sectors such as cement, steel, and chemical production.

In the **2040 Reference scenario**, a storage capacity of 5.6 $MtCO_2$/year is estimated for carbon dioxide removal (CDR) methods, distributed between BECCS and DACCS.

Among the two main technological approaches for direct air CO_2 capture—S-DAC (solid sorbent adsorption) and L-DAC (liquid sorbent absorption)—the L-DAC option is discarded due to its high thermal demand (300–900 °C). Furthermore, DACCS faces the inherent challenge of the low atmospheric CO_2 concentration (approximately 0.04%), which significantly increases energy and operational requirements. By contrast, BECCS benefits from processing gas streams with higher CO_2 concentrations, reducing both energy intensity and capture costs. As detailed in Section 3.5, Spain presents a significant potential for BECCS deployment, particularly linked to biogas and biomethane plants, which could become a strategic pillar of national-scale CDR implementation.

Box 6. SENSITIVITY ANALYSIS on the realistic 2050 CDR potential

Given that storage represents a significant constraint, a sensitivity analysis was conducted to assess the potential deployment of CDR in the Ambitious 2050 scenario under the assumption that the entire storage capacity would be allocated exclusively to CDR rather than to both CDR and CCS.

Under this assumption, the projected annual injection for CDR would be approximately 40 $MtCO_2$/year.

	$MtCO_2$/year	Notes
BECCS (Combustion)	17.9	Considering 70% of the storage available for BECCS
BECCS (Anaerobic Digestion)	10.1	
Electrochemical DACCS	8.1	Considering 30% of the storage available for DACCS
Low-temperature DACCS	3.9	
High-temperature DACCS	0	High-grade heat is assumed to be fully directed to industry, leaving none for CDR.

Table 19. CDR realistic potentials assuming no CO_2 storage limit.

Resulting in a total CDR potential of **88.24 $MtCO_2$/year** instead of the 69.64 $MtCO_2$/year estimated in the 2050 Reference scenario.

Accordingly, a storage capacity allocation of **90 % for BECCS (5.04 $MtCO_2$/year)** and 10 % for DACCS (0.56 $MtCO_2$/year) is proposed. This distribution reflects a prudent and realistic strategy, prioritizing technical and economic efficiency in the deployment process.

In the **2050 Reference scenario**, the national storage capacity attributable to BECCS and DACCS is estimated at 15.95 $MtCO_2$/year.

Regarding estimated costs, carbon capture through BECCS will be considered at an average value of 105 EUR/tCO_2 based on *The Climate Drive* (2023) —a report explained by the *Forest Solutions Group* in partnership with *McKinsey Sustainability*— within the expected 2050 large-scale deployment range of 50–160 EUR/tCO_2[135]. In contrast, direct air capture (DACCS) an average estimation of 127.5 EUR/tCO_2 will be considered, consistent with the expected 2050 range of 85–170 EUR/tCO_2, reported by the *World Economic Forum* (2023)[136].

Given that BECCS offers a lower cost per ton of CO_2 removed compared to DACCS, and considering the technical limitations of DACCS, it is reasonable to prioritize storage capacity allocation to BECCS, thereby promoting a more efficient and economically viable deployment of CDR methods. To support a realistic and cost-effective deployment pathway, a allocation of storage capacity is proposed **80 % for BECCS (12.76 $MtCO_2$/year) and 20 % for DACCS (3.19 $MtCO_2$/year)**. This distribution accounts for BECCS's technical and economic advantages while preserving DACCS's contribution, ensuring a diversified portfolio of negative emission methods.

In the 2050 **Ambitious scenario**, storage capacity would expand to 21.45 $MtCO_2$/year. In this context, a somewhat greater penetration of DACCS is anticipated, driven by its increasing technological maturity, the gradual reduction in capture costs, and its ability to operate independently of biogenic or industrial sources. This approach is particularly relevant in regions with limited availability of sustainable biomass.

Therefore, a distribution of **70% of total capacity for BECCS (15.02 $MtCO_2$/year) and 30% for DACCS (6.43 $MtCO_2$/year)** is proposed. This scenario would represent a balanced carbon removal system, less dependent on a single technology and more resilient to uncertainties related to biomass availability, energy costs, or siting constraints.

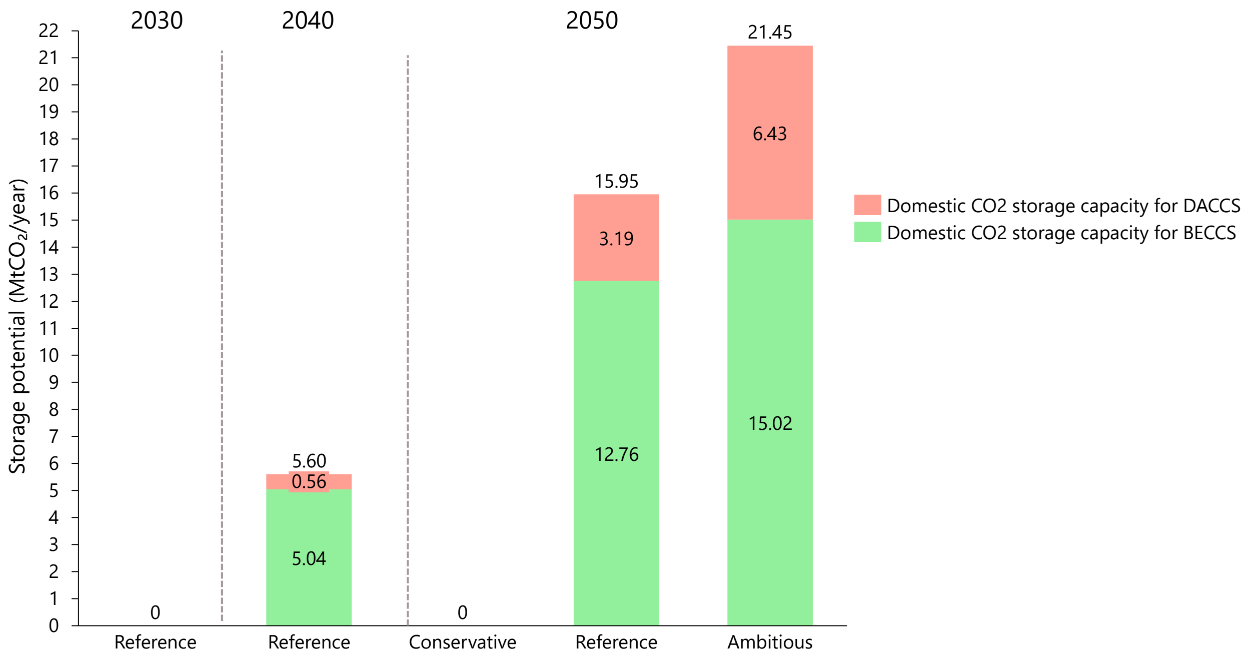


Figure 32. Estimated distribution of national CO_2 storage capacity for BECCS and DACCS across realistic scenarios

In-situ mineralisation

Currently, there is no evidence of operational in-situ mineralisation of CO_2 at scale in Spain. For this reason and following the reasoning described in section 3.7.3, it is assumed that there will be no mineralisation in 2030 and in the 2050 Conservative scenario. A small amount of mineralisation is assumed to be available in the 2040 Reference scenario focussing mostly on pilot projects and small hubs to build experience (Figure 33). By 2050, storage potential is expected to range from minimal (Reference scenario) to over 1.5 $MtCO_2$/year in the Ambitious scenario, with deployment dependent on policy, investment, and public acceptance.

Ex-situ mineralisation

Although there is currently nothing significant at the national level in terms of carbon mineralisation, some companies such as Petronor and O.C.O, in collaboration with companies from the REPSOL group, have conducted pilot projects such as AggregaCO₂, through which they have managed to capture around 2,200 tons per year.[77]

In line with section 3.7.3 and the AggregaCO₂ project, the realistic potential of ex-situ mineralisation considers only CKD and steel slag. If 10% of the total available residues are effectively collected, this would amount to approximately 0.5 Mt per year by 2030. Based on an average CO_2 uptake of 50 kg of CO_2 per tonne of mineral, as reported in source[73], this would correspond to a potential of about **0.025 $MtCO_2$/year in 2030**. The storage potential is expected to increase between to **0.129 and 0.229 $MtCO_2$/year by 2040** and between to **0.446 and 0.846 $MtCO_2$/year by 2050** for the Reference scenario (Figure 33). The 2050 **Conservative scenario** assumes that ex-situ mineralisation would not increase, resulting in the **same amount as in 2030**. In the 2050 **Ambitious scenario**, an expansion of pilot projects and initial industrial scaling is considered, increasing the storage potential of ex-situ mineralisation to **0.05 $MtCO_2$/year**.

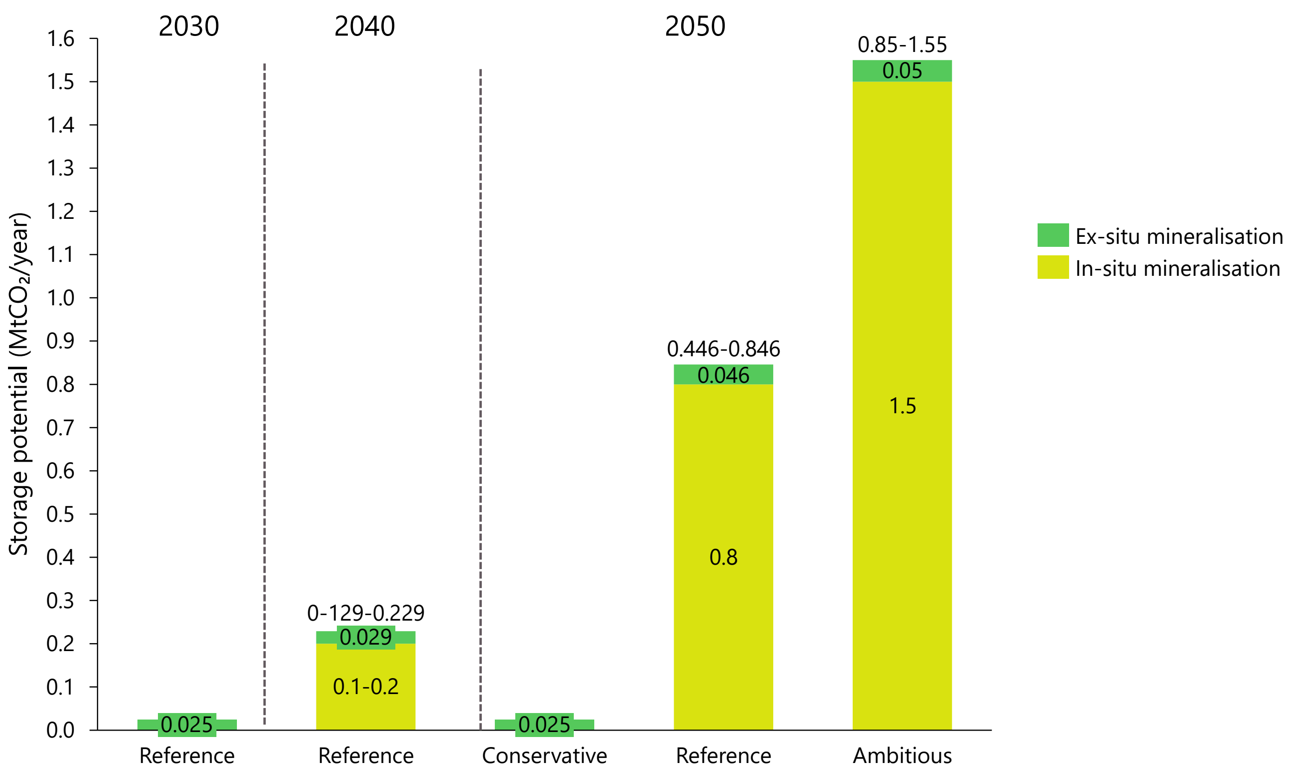


Figure 33. Estimated potential for mineralisation across realistic scenarios

7.4 A like-for-like net-zero pathway for Spain

The presented scenarios not only contemplate a series of actions towards CDR deployment, but are also accompanied by concrete commitments from all sectors to lower and abate emissions. The economic, political, technological, and social design to make these scenarios a reality must comply with the *like-for-like* principle[137], which implies that emissions and removals should have a common link derived from the structure of the natural carbon cycle. ***Biogenic*** emissions that derive from the biosphere (agriculture, land-use changes, bio-waste), and are short-lived, can be removed through temporary removals such as nature-based and agricultural CDR methods. On the other hand, long-lived emissions caused by human intervention (industry, power and energy, fossil fuels, non-bio waste), namely ***Fossil***-based, must be abated through durable CDR methods (BECCS, biochar, DACCS). Complying with the like-for-like principle means both temporary and durable CDR methods must be scaled up in parallel to match the corresponding biogenic and fossil emissions.

The residual emissions that must be removed by 2050 according to the Long-term strategy are **29 $MtCO_2$/year**, of which **10 $MtCO_2$** can be classified as ***fossil***, and **19 $MtCO_2$** as ***biogenic***.[138]

In the 2050 Reference scenario, nature based low-performance CDR methods - including bio based products, agricultural measures, and forest and ecosystem management - deliver **34 $MtCO_2$/year** of removals without drawing on the projected 14 $MtCO_2$ forest sink. This comfortably satisfies the like for like requirement for biogenic emissions. The 2050 Ambitious scenario performs even better: **41 $MtCO_2$/year** of nature based removals exceed the 19 $MtCO_2$ of biogenic residual emissions, again without relying on the natural sink of 32.2 $MtCO_2$/year. By contrast, the 2050 Conservative scenario fails to match either biogenic or fossil residual emissions.

Permanent CDR methods – mostly BECCS, DACCS, and biochar - provide sufficient durable removals to neutralise fossil emissions in both the 2050 Reference and Ambitious scenarios, delivering **18 $MtCO_2$** and **28 $MtCO_2$**, respectively. As shown in Figure 34, the scenario design therefore adheres to the like for like principle across in both the Reference and Ambitious scenarios.

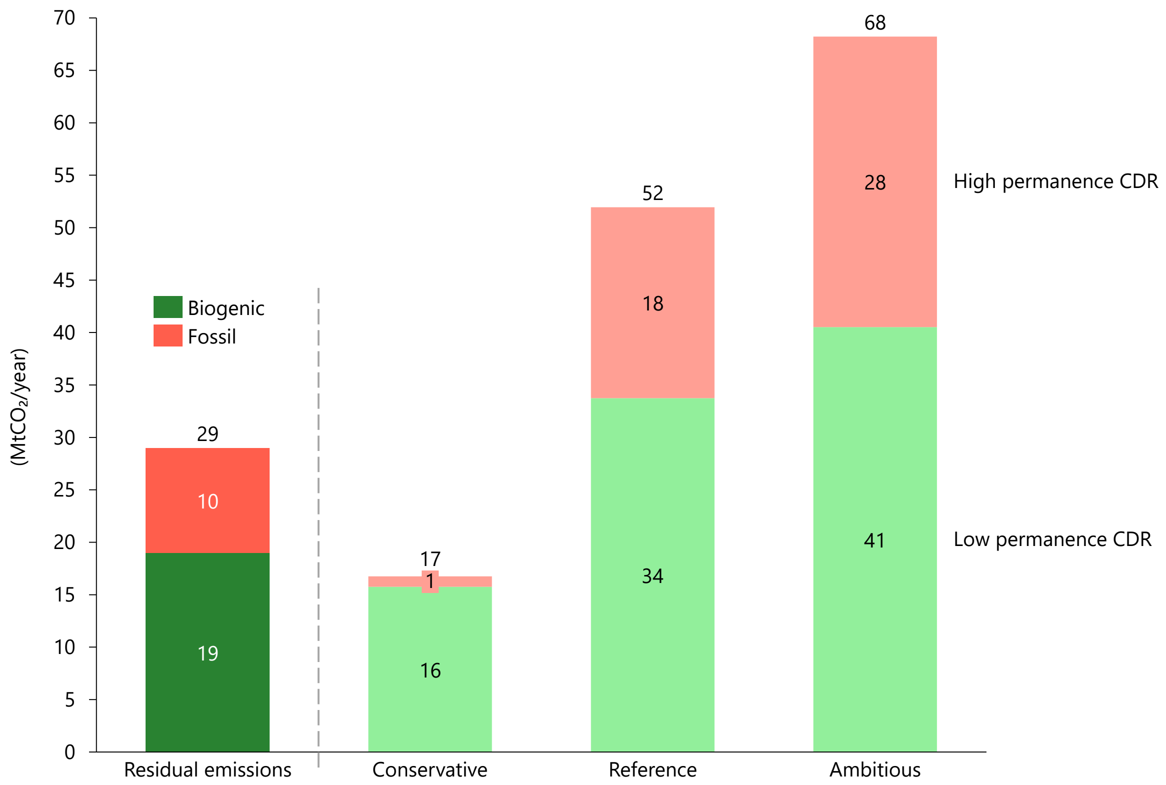


Figure 34. Like-for-like principle across the Conservative, Reference and Ambitious scenarios compared to the expected residual emissions in 2050.

Conclusions

Spain possesses a diverse portfolio of CDR opportunities, with a theoretical potential of removing **196 $MtCO_2$ per year by 2050**, assuming full resource mobilisation without social or economic constraints. This potential is dominated by ecosystem-based methods, followed by geochemical options, whereas synthetic methods such as DACCS are relevant but more modest, mainly limited by available CO_2 storage capacity. This upper-bound estimate reflects a technically possible but practically unattainable level of mobilisation, serving as a benchmark for understanding Spain's resource endowment.

A significant potential built on a portfolio of CDR methods

When realistic constraints are introduced, the country's realistic CDR potential (excluding the natural sink) decreases to **16.6 Mt CO_2** in the Conservative scenario, to **51.8 Mt CO_2** in the Reference scenario and reaches **68.2 $MtCO_2$** removals per year in 2050 in the Ambitious scenario by 2050. In all cases, the contribution of ecosystem management remains predominant, with values around 15–40 $MtCO_2$, followed by biomass-based conversion methods such as BECCS and biochar (1–21 $MtCO_2$) and electrochemical DACCS (up to 6.5 $MtCO_2$). The combined share of these three categories exceeds 90% of total removals. Enhanced weathering contributes marginally mainly through the reuse of mineral waste fractions, while marine options such as *Posidonia* restoration or ocean alkalinity enhancement offer only localised potential. Compared to the theoretical ceiling, this realistic range suggests that around 8–35% of Spain's theoretical potential could be mobilised under favourable policy, investment, and societal conditions.

Spatially, the most promising CDR hotspots align with regions of high biomass productivity, mineral resource concentration, and available non-arable land. Andalusia, Galicia, and the Canary Islands stand out for mineral-based options such as basalt and dolomite weathering, while Castile-León, Extremadura, and the Ebro Valley present extensive land availability for forest restoration and soil carbon practices. Coastal and marine areas of the Balearic Islands and the Mediterranean littoral may offer niche opportunities for *Posidonia* farming, provided that biodiversity constraints are respected. The strategic co-location of CDR facilities with planned CO_2 transport and storage infrastructure - such as in Tarragona and the Cantabrian Basin - would enhance cost efficiency and facilitate the creation of an integrated carbon management network.

Low societal readiness, missing policies and slow development of transport and storage

Despite these opportunities, several limitations hinder large-scale deployment. The main constraint is the lack of a dedicated national strategy and regulatory framework for CO_2 management (CDR+CCS), which undermines investor confidence and prevents the development of permanent CO_2 storage hubs. The limited geological storage capacity currently characterised restricts the expansion of BECCS and DACCS, both of which depend on secure storage solutions. Other structural barriers include competition for land and biomass resources, fragmented governance among ministries, and the absence of financial mechanisms to incentivise early deployment. Technological immaturity and high operational costs further delay the scaling of synthetic methods. From a social standpoint, low public awareness of CDR, combined with a strong preference for nature-based solutions, indicates that communication and participation strategies will be essential to ensure legitimacy and acceptance.

Spain's social and institutional context adds further nuance to the deployment outlook. The citizen panel and stakeholder consultations revealed a consistent pattern: widespread trust in ecosystem-based approaches, moderate acceptance of mineral and bio-based pathways, and scepticism toward industrial and ocean-based methods. These perceptions are influenced by Spain's environmental culture, where reforestation, sustainable agriculture, and circular use of industrial residues resonate strongly with existing policy narratives. This implies that the design of the national CDR roadmap should prioritise actions that align with these societal preferences by integrating CDR into rural development programs, leveraging forest and soil management initiatives, and coupling technological solutions with visible co-benefits for biodiversity, employment, and regional equity.

Untapped potential

The realistic scenarios presented in this study were designed to be feasible with high confidence in the near future, adopting conservative assumptions. As a result, some of the CDR potential of Spain was left untouched for now, as is the case with mafic bedrock for ERW, but could become actionable in the future, subject to evolution in public support translated into new regulations.

Two main avenues to create additional CDR potential were most likely underestimated in this report, given the lack of data on efficiency and/or acceptability. The first is the use of carbonate rocks for ERW or alternative pathways like riverine alkalinity management. Shall these methods be further demonstrated and the required policy put in place, the CDR potential of Spain could rise significantly given the abundance of these feedstocks. The second is related to OAE and DOCCS, in particular when leveraging existing coastal water treatment infrastructure. Here again, Spain has a relatively large infrastructure providing opportunities if the perception of these methods evolves and allows the necessary policies to be passed.

Beyond the end date of this assessment (2050), Spain will most likely continue to develop its geological storage capacity, unlocking further potential CCS empowered CDR like DACCS or DOCCS.

A key decade

Spain has a significant potential for CDR but cannot compress the lead time to deploy these new activities at scale. The decision made in the coming 5 to ten years are those that truly matter to deploy CDR in time for keeping global warming in check.

This report is accompanied by a policy roadmap codesigned with national stakeholders and listing the key actions and changes that need to occur for the estimated CDR potential to be realised.

Having the means of removing important amounts of carbon from the atmosphere is both a comparative advantage and a responsibility.

Annex A. Realistic CDR potentials table

CDR method	Realistic CDR potential (2030)	Realistic CDR potential (2040)	Realistic CDR potential (2050)			Key assumptions
			Conserv-ative	Refer-ence	Ambit-ious	
Biomass conversion	**19.9**	**26.8**	**15.6**	**33.6**	**40.3**	
Afforestation/ reforestation	0.3	2	1.95	3.9	6.5	The 2050 Reference scenario is based on the objective of reforesting 0.6 Mha as per Spanish Forestry Strategy[24]. Conversion factor used: 6.5 tCO_2/ha (based on the INIA-CSIC and MITERD study on young reforestation)[90].
Improved Forest Management (IFM)	1.9	5.7	0	9.5	12.4	Assumed that IFM could increase similarly to forest certification (PEFC and FSC). Conservative and ambitious scenarios have been established for 2050 based on the trend scenario[139], with a 30% increase or decrease.
Agroforestry	0.4	1.2	0.38	1.9	2.3	Conversion factor used: 2.74 tCO_2/ha based on the seminar *"La dehesa: definición, producción del arbolado y tendencias de la gestión silvopastoral,"* presented by the Spanish Society of Forest Sciences and the University Institute for Sustainable Forest Management, UVa-INIA[30].
Cropland management (total)	11.6	12	8.9	12.25	13.4	The reference scenario is based on the National Energy and Climate Plan (PNIEC) which promotes the spread of these two practices in its "Measure 1.25 Agricultural Sinks"[129]. Conversion factors of direct seeding in annual crops and vegetation cover in woody crops from the "4 per 1000 Initiative: soil organic carbon as a tool for climate change mitigation and adaptation in Spain"[29].
Cropland management (direct seeding and zero/ conservation tilling)	*3.2*	*3.3*	*2.5*	*3.4*	*3.7*	*The Spanish Government considers direct seeding and zero or conservation tillage to be one of the solutions for increasing CO_2 capture in annual arable land.*
Cropland management (cover crops)	*8.4*	*8.7*	*6.5*	*8.9*	*9.7*	*The Spanish Government considers vegetation cover to be one of the solutions for increasing CO_2 capture in wooded arable land.*
Pasture management	5.7	5.7	4.1	5.6	*5.3*	FEGA is beginning to highlight the critical role of pasture management. Effective stewardship of existing pastures is essential to sustaining the health and resilience of this ecosystem. Removals from pasture management are proportional to projected grassland area, which is assumed to be 5.28 Mha (excl. *dehesa*). Conversion factor used: 1.1 tCO_2/ha/year[93].
Wetland restoration	0.05	0.06	0.07	0.14	0.2	Considering Spanish restoration plans to restore 20 kha by 2030 and 50 kha by 2050.

continued>

CDR method	Realistic CDR potential (2030)	Realistic CDR potential (2040)	Realistic CDR potential (2050)			Key assumptions
			Conserv-ative	Refer-ence	Ambit-ious	
Coastal revegetation	0	0.12	0.20	0.22	0.24	Estimations according to Red Eléctrica's report. In a realistic 2050 scenario where *Posidonia* degradation halts and restoration advances, up to 20% of degraded meadows could be recovered, primarily within protected marine zones.
Biomass conversion	**1**	**7**	**1**	**15**	**21.3**	
BECCS (Combustion)	0	3.7	0	8.2	9.6	BECCS is excluded from the 2030 and 2050 conservative scenarios due to lack of CO_2 storage. In 2040, 90% of available storage is assumed for BECCS; in 2050, 80% in the reference scenario and 70% in the ambitious scenario.
BECCS (Anaerobic Digestion)	0	1.3	0	4.6	5.4	
Biochar	1	2	1	2.2	6.1	Considering that 50% of the biomass from thermochemical processes goes to pyrolysis and that 50% of this is recovered for CDR. Of that, for 2050, 20% for conservative scenario, 50% for reference scenario, 100% for ambitious.
Durable biobased products	0.18	0.18	0.18	0.18	0.18	As data and projections for 2040 and 2050 are insufficient to provide robust estimates, the estimated value for 2030 has also been used as a proxy for the years 2040 and 2050 to maintain consistency.
Geochemical	**0.002**	**0.002**	**0.003**	**0.008**	**1.013**	
ERW (total)	0.002	0.002	0.003	0.008	0.013	
with limestone	*0*	*0*	*0*	*0*	*0*	*The realistic scenarios exclude dolomite and limestone due to insufficient bibliographic evidence of their effectiveness and therefore consider only basalt for ERW.*
with dolomite	*0*	*0*	*0*	*0*	*0*	
with basalt	*0.002*	*0.002*	*0.003*	*0.008*	*0.013*	*Assumption that 4.3 t of mineral captures 1 t CO_2, and that up to 10% of waste dust is effectively collected.*
with mafic rocks	*0*	*0*	*0*	*0*	*0*	*Between now and 2050, impossible to open new mines in currently protected areas given current levels of awareness and acceptance of CDR.*
OAE	0	0	0	0	1	Due to social rejection, OAE is assumed to be implemented only in the most ambitious scenario and only with minimal potential.
Synthetic	**0**	**0.6**	**0**	**3.2**	**6.4**	
Electrochemical DACCS	0	0.5	0	2.3	4.3	DACCS is not considered for 2030 and 2050 conservative scenario, as there will be no storage available for CDR. Assuming 10% of the storage available for 2040; 20% for 2050 Reference scenario and 30% for 2050 ambitious scenario.
Low-temperature DACCS	0	0.1	0	0.9	2.1	
High-temperature DACCS	0	0	0	0	0	High-grade heat is assumed to be allocated exclusively to industry, with no residual left for CDR.
Total	**20.9**	**34.40**	**16.60**	**51.81**	**69.01**	

Table A.1. Estimated realistic CDR potential in Spain across 2030, 2040 and the three 2050 scenarios with key assumptions. Data in $MtCO_2$.

Annex B: Resource availability in the realistic CDR scenarios

Resource	2030	2040	2050			Key assumptions
			Conserv-ative	Refer-ence	Ambit-ious	
Energy (TWh)						
Renewable electricity	15.5	19	22	26.5	31	Only export-bound electricity is assumed to be available for CDR.
Waste heat (low grade)	11.82	10.42	6.03	9.04	12.05	Only low-grade heat is used for CDR. High-grade heat is assumed to be fully directed to industry, leaving none for CDR.
Water (bcm)						
Fresh water	0.02	0.03	0.02	0.04	0.05	Low-temperature DACCS is assumed to consume 1000 L per ton of CO_2, with water supplied from northern regions where availability is high.
Salt water	0.00	0.6	2.28	2.98	3.68	A water requirement of 2000m3/t of CO_2 was assumed for all CDR methods that use saltwater. Sea water is only used as a refrigerant and therefore after the thermal exchange has happened, it is returned to the sea.
Land (Mha)						
Annual arable land	1.02	1.06	0.79	1.08	1.18	Cropland is expected to decrease because of low profitability, rural abandonment and replacement by forestland.
Permanent arable land	1.49	1.54	1.14	1.57	1.71	
Forestland	0	2.26	2.64	3.77	4.90	Spain's forestry strategy targets 0.6 Mha of reforestation by 2050, increasing forestland.
Grassland	5.42	5.89	4.13	6.40	6.64	Grasslands are expected to decrease due to the decline of extensive livestock farming and natural reforestation of abandoned lands. *Dehesa* regeneration is planned to strengthen agroforestry.
Peatlands (kha)	0	0.44	0.73	0.91	0.97	Peatland conservation projects are assumed to remain scarce, with little or no new initiatives expected in the near term.
Underwater surfaces for seagrass restoration (kha)	0	2.48	9.92	12.4	13.19	Spain's strategy on seagrass restoration is focused on preventing further degradation.
Biomass (MtDM)						
Biomass for BECCS - combustion	13.1	15.8	13.2	15.2	22	Considering 40% BECCS for 2030; 60% for 2040. For 2050: 60% for Conservative scenario. For reference scenario biogenic CO_2 that can be used for e-fuels is deducted from the potential of BECCS. And for ambitious the same amount as theoretical
Biomass for BECCS - anaerobic digestion	3.8	8	10.5	11.5	17.5	
Biomass for biochar	1.5	2.71	1.5	3	6.1	Assuming 50% of biomass from thermochemical processes goes to pyrolysis, and 50% is recovered for CDR. By 2050, this depends on the scenario: 25% (Conservative), 50% (Reference), 100% (Ambitious).

continued>

Resource	2030	2040	2050			Key assumptions
			Conserv-ative	Refer-ence	Ambit-ious	
Minerals						
Limestone	2.052	2.131	2.211	3.883	5.556	Assuming only the waste fractions are used (Table 7) with a 10% collection rate. Same reaction rates than those in Table A.1.
Dolomite	0.29	0.389	0.523	0.639	0.760	
Basalt	0.009	0.01	0.011	0.034	0.056	
Cement	0.318	0.378	0.439	0.536	0.633	
Steel slag	0.190	0.197	0.204	0.377	0.550	
CO_2 storage (Mt)						
Geologic reservoirs	0	5.6	0	15.95	21.45	Based on a bottom-up approach, given the lack of a Spanish strategy.
Mineralisation	0.03	0.03	0.03	0.04	0.05	Assuming that only waste cement and steel slag would be used.

Table B.1. Summary of resource and feedstock availability for CDR in Spain across 2030, 2040 and 2050.

Annex C: Biomass

C1. Current biomass consumption pathway for Spain

Biomass categories	Mt
Forest biomass total	**9.08**
Bark	0.258
Black liquor and crude resin oil	2.084
Branches and tree tops (including chip format)	2.176
Charcoal	0.024
Other forest residues	0.741
Recycled wood	0.036
Roundwood for fuel use (including firewood)	1.666
Tree stumps (including chip format)	0.070
Wood chips, sawdust and other wood particles	1.064
Wood pellets and briquettes	0.960
Agricultural/Agro-industrial biomass total	**4.18**
Cereal straw	0.038
Coffee grounds	0.008
Grape pomace	0.061
Nut shells	0.127
Olive pit	0.392
Olive pomace	1.469
Olive wood (including pruning residues and plantation removal)	0.402
Other plant materials and residues from agricultural crops	1.239
Pine cones	0.062
Pine nut shells	0.001
Rice husk	0.003
Vine shoots (including pruning residues and plantation removal)	0.036
Woody energy crops	0.340
Biogenic waste (livestock, sewage sludge, MSW, industrial waste, etc.) total	**3.77**
Livestock	0.087
Residual sludge	0.067
Other bio-liquids (e.g., vegetable oil, renewable industrial liquid residues)	0.049
Other biomass fuels	1.137
Other livestock residues	0.016
Other non-renewable industrial residues	0.138
Other renewable solid industrial residues	0.259
Industrial residues, non-renewable fraction	0.201
Industrial residues, renewable fraction	0.099
MSW non-renewable fraction	0.538
MSW Renewable	1.182

Table C.1.Current biomass consumption breakdown[32].

C2. Distribution of biomass to the different valorisation pathways and energy conversion

The different biomass feedstocks have been distributed across the main valorisation pathways - combustion, anaerobic digestion and thermochemical processes (such as pyrolysis). The percentages assigned to each valorisation pathway reflect physicochemical characteristics of each type of biomass and typical uses in Spain, offering an indicative approximation that may vary by region, technology, and market conditions. The same assumptions have been applied to allocate biomass in both theoretical and realistic CDR potential calculations.

Biomass Category	Valorisation pathways 2030	Projected 2030 (MtDM)	Valorisation pathways 2040	Projected 2040 (MtDM)	Valorisation pathways 2050	Projected 2050 (MtDM)
Forestry biomass	Combustion: 85% Anaerobic Digestion: 0% Thermochemical processes: 15%	12	Combustion: 70% Anaerobic Digestion: 0% Thermochemical processes: 30%	11.9	Combustion: 60% Anaerobic Digestion: 0% Thermochemical processes: 40%	11.4
Agricultural/ agro-industrial biomass	Combustion: 65% Anaerobic Digestion: 25% Thermochemical processes: 10%	20	Combustion: 40% Anaerobic Digestion: 35% Thermochemical processes: 20%	20.8	Combustion: 40% Anaerobic Digestion: 40% Thermochemical processes: 20%	22
Biogenic wastes (livestock manure and slurry, sewage sludge, MSW, industrial waste, etc.)	Combustion: 50% Anaerobic Digestion: 35% Thermochemical processes: 15%	15	Combustion: 35% Anaerobic Digestion: 45% Thermochemical processes: 20%	15.6	Combustion: 15% Anaerobic Digestion: 65% Thermochemical processes: 20%	16.5
Total		**47**		**48.3**		**49.5**

Table C.2. Biomass classification by valorisation pathways 2030, 2040 and 2050 in Spain.

	Projected Spain 2030 (MtDM)	Projected Spain 2040 (MtDM)	Projected Spain 2050 (MtDM)
Combustion	30.7	23.2	18
Anaerobic Digestion	10.3	14.3	19.4
Thermochemical processes (Pyrolisis/Gasification)	6.1	10.9	12.2
Total	**47**	**48.3**	**49.5**

Table C.3. Amount of biomass available for CDR allocated to each valorisation pathway.

Biomass Category	Mtoe/Mt	Mtoe to TWh
Forestry biomass	0.30	1 Mtoe = 11.63 TWh
Agricultural/agro-industrial biomass	0.30	
Biogenic wastes (livestock manure and slurry, sewage sludge, MSW, industrial waste, etc.)	0.20	
Total	**47**	**48.3**

Table C.4. Factors used to convert biomass into energy units.

Annex D: Exponential curves to estimate CO_2 injection rates

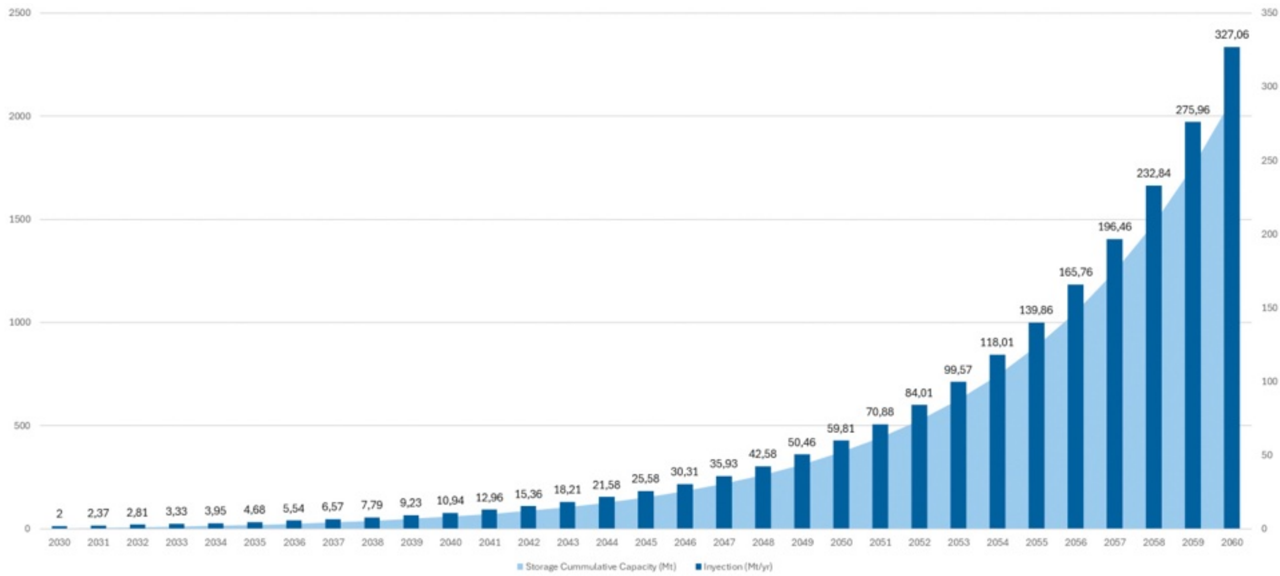


Figure D.1. Exponential 2060 curve developed as part of this study.

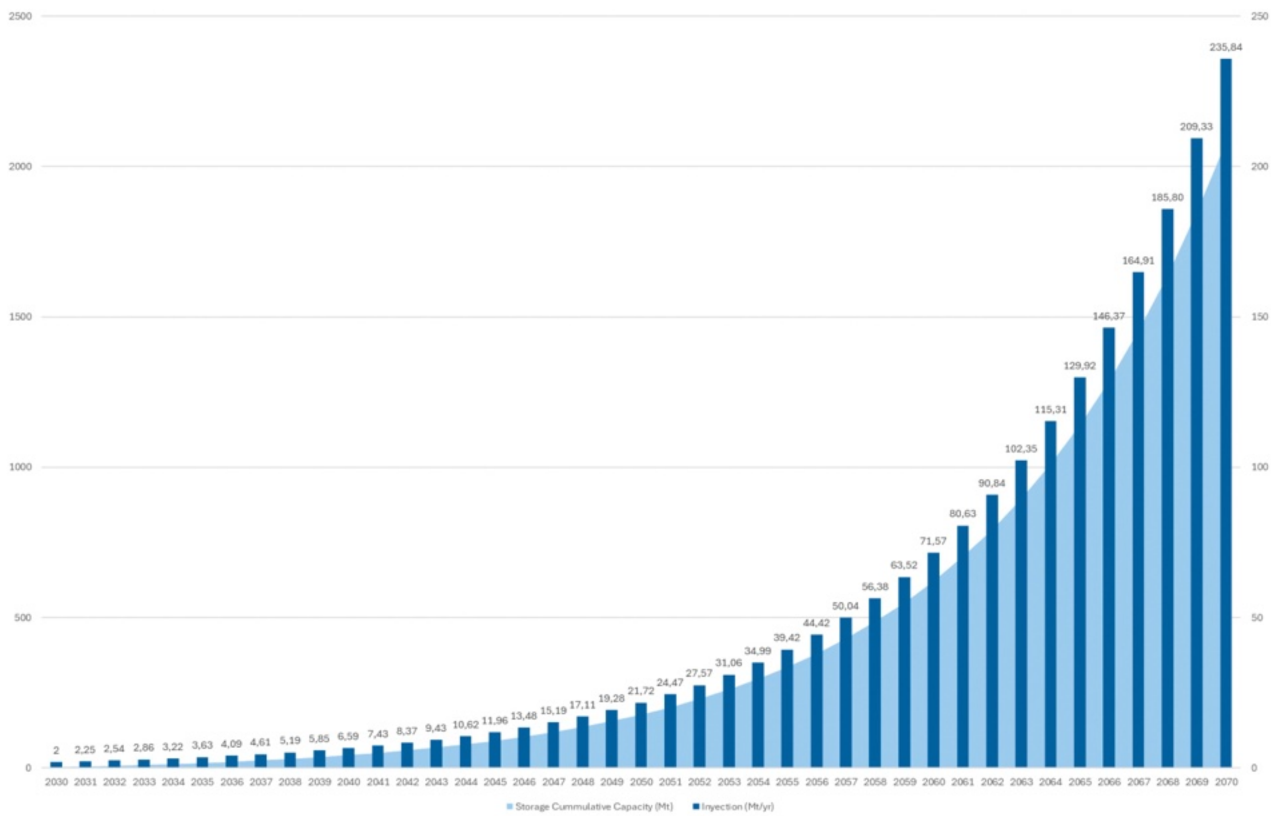


Figure D.2. Exponential 2070 curve developed as part of this study.

Annex E: Additional maps from Chapter 3

Figure E.1 Spain's climate map according to Köppen.

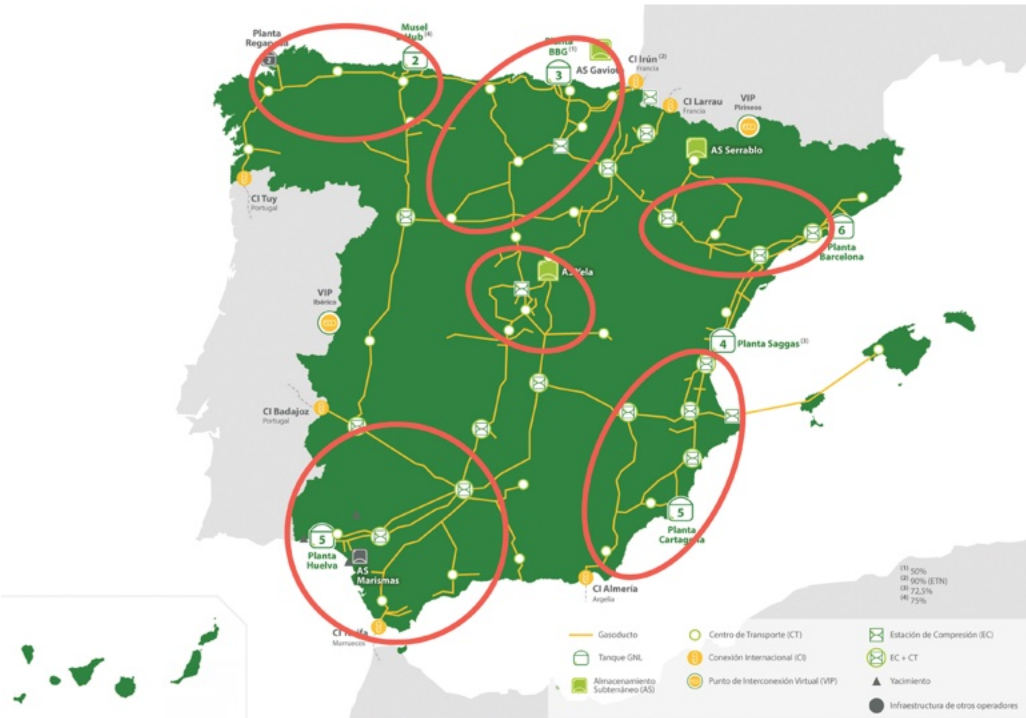


Figure E.2. LNG infrastructure and CO_2 hubs identified by Enagás.

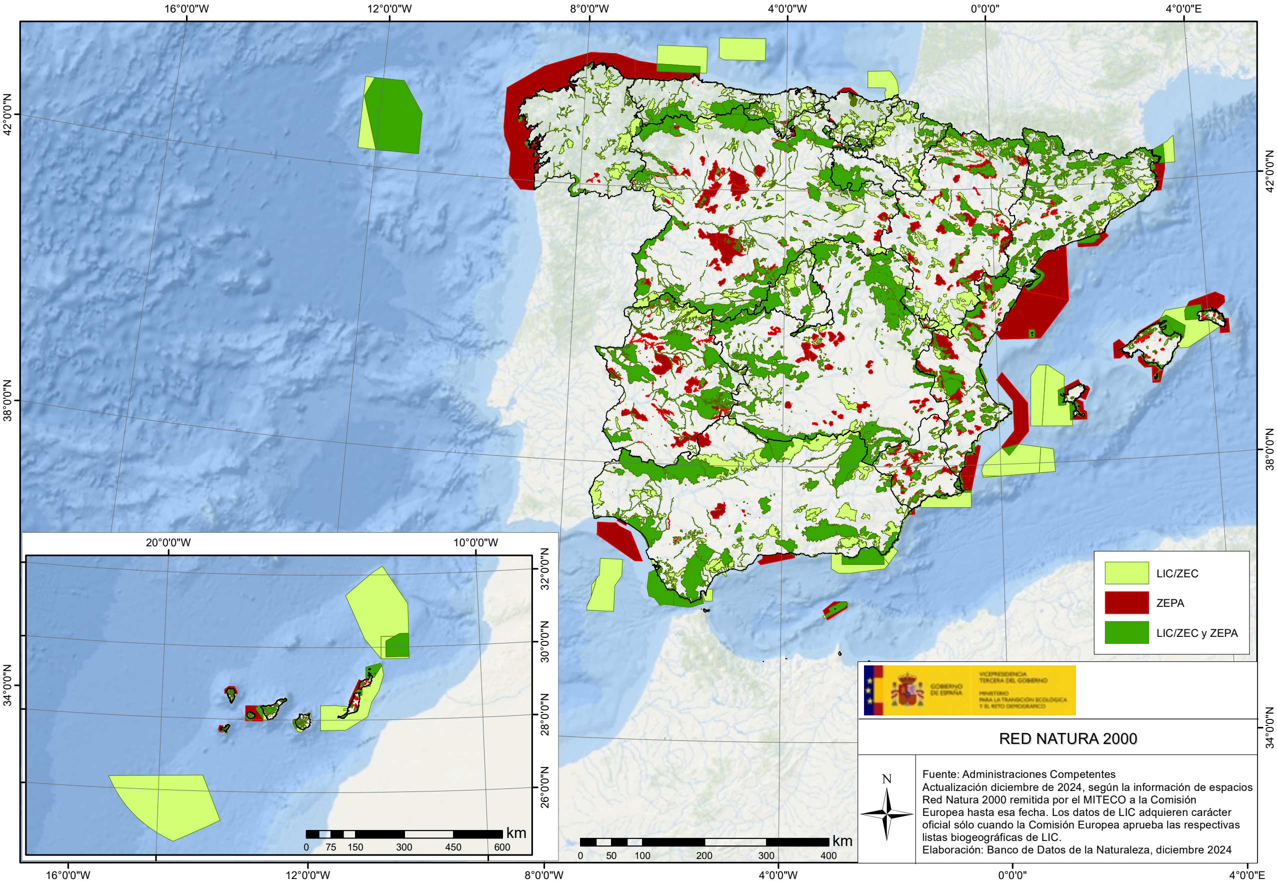


Figure E.3. Protected areas in Spain[140].

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ABOUT

Carbon Gap

Carbon Gap was established to be Europe's first philanthropically funded environmental advocacy organisation, focusing exclusively on CDR. The mission is to ensure that Europe becomes a leader in developing and deploying CDR solutions at scale in a safe and equitable manner to preserve a stable climate. Carbon Gap is coordinating the delivery of the project that has produced this report.

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Global Factor is an international firm specialising in innovative and sustainable solutions in climate change, energy, green growth, climate finance, and carbon markets. With over 20 years of experience, 1,400+ projects in 44 countries, and a multidisciplinary team of 70+ experts, the company combines technical, policy, and financial expertise. It supports governments and the private sector in designing and implementing decarbonization strategies, NDCs, and climate finance frameworks. Trusted by leading international institutions such as the World Bank, ADB, IDB, and the EU, Global Factor delivers impactful, context-specific solutions worldwide

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