



CEEES DELIVERABLE D6.2

TRANSVERSAL INTERSECTORAL DECARBONISATION AS GHG BALANCE

Summary:

Deliverable 6.2 studies CO₂ sources, transport and cycle maintenance to enhance the benefits for CEEES projects. An evaluation of the potential for transversal intersectoral decarbonisation, especially in hard-to-decarbonise sectors, such as the cement sector, and the possibility of negative emissions to be achieved is done. Combination with CO₂ industrial uses is also checked to stabilise GHG balances.

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**Funded by
the European Union**

Title:		Transversal intersectoral decarbonisation as GHG balance	
Lead beneficiary:		IGME-CSIC	
Other beneficiaries:		HZDR	
Due date:		October 2024	
Nature:		Public	
Diffusion:		Public	
Status:		Live document (preliminary version)	
DOI:			
License information:		It is recommended to use a Creative common license: https://en.wikipedia.org/wiki/Creative_Commons_license	
Recommended Citation:		Canteli, P.; García-Crespo, J.; Fogel, S.; Unger, S. (2024) The Horizon Europe CEEGS project: Deliverable 6.2 - Transversal intersectoral decarbonisation as GHG balance, IGME-CSIC, HZDR.	
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Document code:		CEECS_D.6.2	
Revision history	Author	Delivery date	Summary of changes and comments
Version 01	JGC/SF	22.10.2024	First version
Version 02	JGC/SF	XX.10.2024	Public version
Final version			

Approval status				
	Name	Function	Date	Signature
Deliverable responsible	Dr. S. Fogel (HZDR)	Editor	23.10.2024	
WP leader	Dr. P. Canteli (IGME-CSIC)	WP leader	23.10.2024	
Reviewer				
Reviewer				
Project Coordinator	Prof. R. Chacartegui (USE)	Coordinator	XX.10.2024	

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1 Executive summary

Deliverable 6.2 studies CO₂ sources, transport and cycle maintenance to enhance the benefits for CEECS projects, within the task 6.2 of CEECS. The aim of this task is to do an evaluation of the potential for transversal intersectoral decarbonisation, especially in hard-to-decarbonise sectors, such as the cement sector, and the possibility of negative emissions to be achieved is done. Combination with CO₂ industrial uses is also checked to stabilise GHG balances.

This report is the first version to be delivered in an intermediate stage of the project and is intended to be an approach to the possibility of developing the CEECS technology in two areas located in Germany and Spain.

2 Data compilation and analysis

Data used for the analysis belongs to the three main domains of relevant information: greenhouse gas emitters, geological storage sites and infrastructure for the transportation of gases, liquids and solids. A compilation of data has been carried out in this task in order to evaluate the amount of CO₂ emissions and the possibility for storing CO₂ in suitable geological formations underground.

The source of data for CO₂ emitters is the Emissions Trading System (ETS) data repository of the European Union (EU ETS, 2024), contained in the European Union Transaction Log (EUTL). The EUTL is run by the European Commission and its purpose is to check and record all transactions taking place within the trading system. The ETS represents the most prominent measure introduced by the EU to comply with emission reduction targets set under the Kyoto Protocol and the general goal of reducing greenhouse gas emissions. Relevant data on CO₂ emitters within the EU, comprising crucial information with respect to:

- the **operating entities** (e.g. national administrators, account types, company registration numbers, account holder names, operator names, operator addresses, etc.),
- the **actual emitting entities** (e.g. installation IDs, installation names, permit IDs, permit information, installation addresses, main industrial activity classification, etc.) and
- the respective **verified CO₂ emission quantities** for the years 2013 to 2023,

have been collected from the EUTL (EU ETS, 2024) as a part of the third (2013 to 2020) and fourth (2021 to 2030) EU ETS trading phases. The data was collected and compiled for all EU member states that are participating in the ETS/EUTL emission registry.

The available information of the EUTL is not presented in an accessible and user-friendly format suitable for further data analysis. The data was therefore collected based on a tailor-made data-mining tool developed within Python 3.12 utilizing the HTML parser BeautifulSoup 4. Since the original and freely available data of the EUTL webpage only provides a limited availability of geolocations (latitude/longitude) of the respective CO₂ emitters (geolocation only reported for approx. 25 % of all permitted emitters in the EUTL; some of them are incorrect), additional data collection steps were performed to gather the missing geolocations with a reasonable accuracy. Missing geolocations were collected based on multi-step and automated search algorithm incorporating the databases of Open Street Map (OSM) and Google Maps (GM). Based on multiple search runs with different search queries (combinations of the mined EUTL data featuring crucial operator and installation information, e.g. countries, addresses, zip codes, cities and operator/installations names), a fusion data set was compiled, containing the complete geolocations of all reported European CO₂ emitters (approx. 7620 installations). The basic data compilation and analysis scheme is depicted in Figure 1.

Due to considerations regarding dataset completeness, the subsequently presented assessments are exclusively based on the collected EUTL emitter and emission data of the year 2022 for the main countries of interest, Spain and Germany.

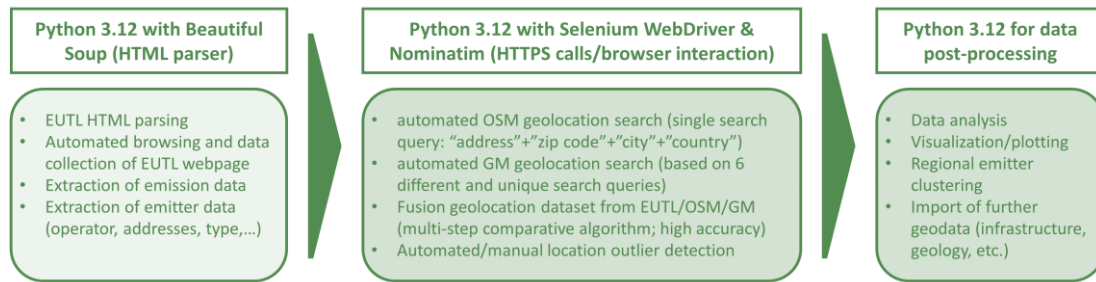


Figure 1: Workflow of the data compilation process for the data acquisition from the EUTL and the respective geolocations of all identified CO₂ emitters in Europe.

Furthermore, the national emission data repository of Spain was utilized for the performed studies, since it provides substantially more data points and information, such as emission type (CO₂, NO_x, etc.), emission quantity and energy requirements, per reported and registered installation (PRTR Spain, 2024). The same approach was employed for the case study of Germany (PRTR Germany, 2024). Apart from that, other georeferenced datasets are employed (e.g. road and rail infrastructure, existing gas network and storage infrastructure, major ports and data of geological surveys for the identification of suitable storage sites and hence regional study clusters). Potential geologic storage sites for CO₂ have been compiled from European projects (e.g. CO2StoP, ESTMAP, Hystories, GSEU) and national projects (e.g. ALGECO2 in Spain). The datasets were updated with data from national geological surveys and include suitable formations for long-term trapping of CO₂ in supercritical state. Data on transport infrastructures is employed for the evaluation and assessment of CO₂ transport pathways/vectors (will be considered for transportation costs in the next version). All national non-georeferenced and georeferenced datasets employed in the present study are compiled in Table 1 alongside their general classification and origin.

Table 1: Employed datasets of the conducted studies.

Dataset description	Source	Ref. year	Georef. (yes/no)	Reference
CO ₂ emitters in the EU (quantities, locations and main industrial activities)	EUTL (extended by own data collection and synthesis according to Figure 1)	2022	yes*	(EU ETS, 2024)
Complementary emission data Spain	PRTR repository Spain	2024	yes	(PRTR Spain, 2024)
Complementary emission data Germany	PRTR repository Germany	2024	yes	(PRTR Germany, 2024)
CO ₂ emitters with offshore locations	ENI, TNO, Norskepetroleum	2024	yes*	(ENI, 2023), (NP, 2024), (TNO, 2023)
Salt structures in Northern Germany	BGR (German Federal Institute for Geosciences and Natural Resources)	2015	yes	(BGR, 2015)
Porous storage units and known geological traps in Europe	EU Project CO2StoP	2014	yes	(CO2StoP, 2014)
Basic vector map backdrop data (world)	Natural Earth	2024	yes	(Natural Earth, 2024)
Natural gas pipeline infrastructure Germany (pipeline diameters)	DIW	2015	yes	(DIW, 2017)
Natural gas storage infrastructure Germany	GSE (Gas Storage Europe)	2021	no*	(GSE, 2024)
Natural gas storage infrastructure Spain	GSE (Gas Storage Europe)	2021	no*	(GSE, 2024)
Porous storage units and known geological traps in Spain	ALGECO2, national geological surveys*	2010	yes	(IGME, 2010)
Rail network Germany	BKG (German Federal Agency for Cartography and Geodesy)	2023	yes	(BKG, 2024)
Road network Europe	Natural Earth	2024	yes	(Natural Earth, 2024)
Major shipping ports Europe	Natural Earth	2024	yes	(Natural Earth, 2024)
Global power plant database	World Resources Institute	2021	yes	(WRI, 2021)
Transmission grid network Germany	SciGRID	2016	yes	(SciGRID, 2024)
Transport, transmission and pipeline infrastructure Spain	IGN Spain	2024	yes	(IGN, 2024)
Saline formations in Spain	IESDB (Iberian Evaporite Structure Database)	2022	yes	(González-Esvertit, 2022)

* respective georeferenced data was collected manually as a part of this study;

* plan de selección y caracterización de áreas y estructuras favorables para el almacenamiento geológico de CO₂ en España.

2.1 CO₂ emitters

The recovered databases contain several items regarding the location of the emitters, industrial activity, year, CO₂ emissions, pollutants, energy consumption and so forth. CO₂ emissions have been collected from the EUTL database, which includes data for allocations at different stages.

Although the original database includes both stationary and non-stationary emitters (road transport, shipping and aviation), only stationary sources are considered. This decision was intentionally made, since CEEGS, as a novel CCUS technology (CO₂ injection with back-production), is based on the utilization of large quantities of captured CO₂ from stationary installations of hard-to-abate industrial processes. Data for several annual time series are available in the emitter's repository. The EUTL accounts for allowances, transfers and verified emissions, and includes an annual reconciliation of allowances and verified emissions. At the time of writing of this report, the most recent and complete time series for verified emissions is for year 2022.

Emitters studied in this report have been selected and grouped by industrial activity based on the allocated activity code. The EUTL data source includes activity codes for installations generated by ETC/ATM, whose methodology is mainly based on information on NACE industry nomenclature codes (NACE: "Nomenclature statistique des activités économiques dans la Communauté européenne") which have been published by the European Commission as part of the preparation of the carbon leakage list for 2015-2019 (ETC/CME¹, 2024; reference to complementary documentation is no longer available).

For the year 2022, 7201 emitting entities reported total CO₂ emissions of approx. 1057.58 Mt for the entire EUTL region. A basic overview over the development of the reported emissions within the EUTL framework is given in Table 2.

Table 2: Reported emissions 2020 to 2023 within the EUTL framework.

Year	Number of reporting installations (-)			CO ₂ emission quantity (Mt/a)		
	Combustion of fuels	Other industrial activities	Total	Combustion of fuels	Other industrial activities	Total
2023	3995	2975	6970	473.50	436.30	909.80
2022	4173	3028	7201	581.10	476.48	1057.58
2021	4278	3045	7323	593.78	505.68	1099.47
2020	4277	3048	7325	533.82	468.56	1002.38

The reporting emitters are dominated by applications/sectors related to the combustion of fuels for the provision of electricity and heat, accounting for more than half of the verified CO₂ emissions within the EUTL framework. However, their future utilization within CCS/CCUS technologies, and therefore potential CEEGS deployments, is unlikely due to regulative/political uncertainties with respect to their actual operation as well as the general shift towards renewable technologies for the supply of electricity and heat. As a consequence, all emissions from the combustion of fuels are excluded from the subsequently presented studies. An overview over the collected emitter locations according to their specific main industrial sectors as defined by the groupings of the NACE/ETS activity codes (will be discussed later in detail) can be found in Figure 2.

¹ ETC/CME: European Topic Centre on Climate change mitigation and energy. European Environment Agency.

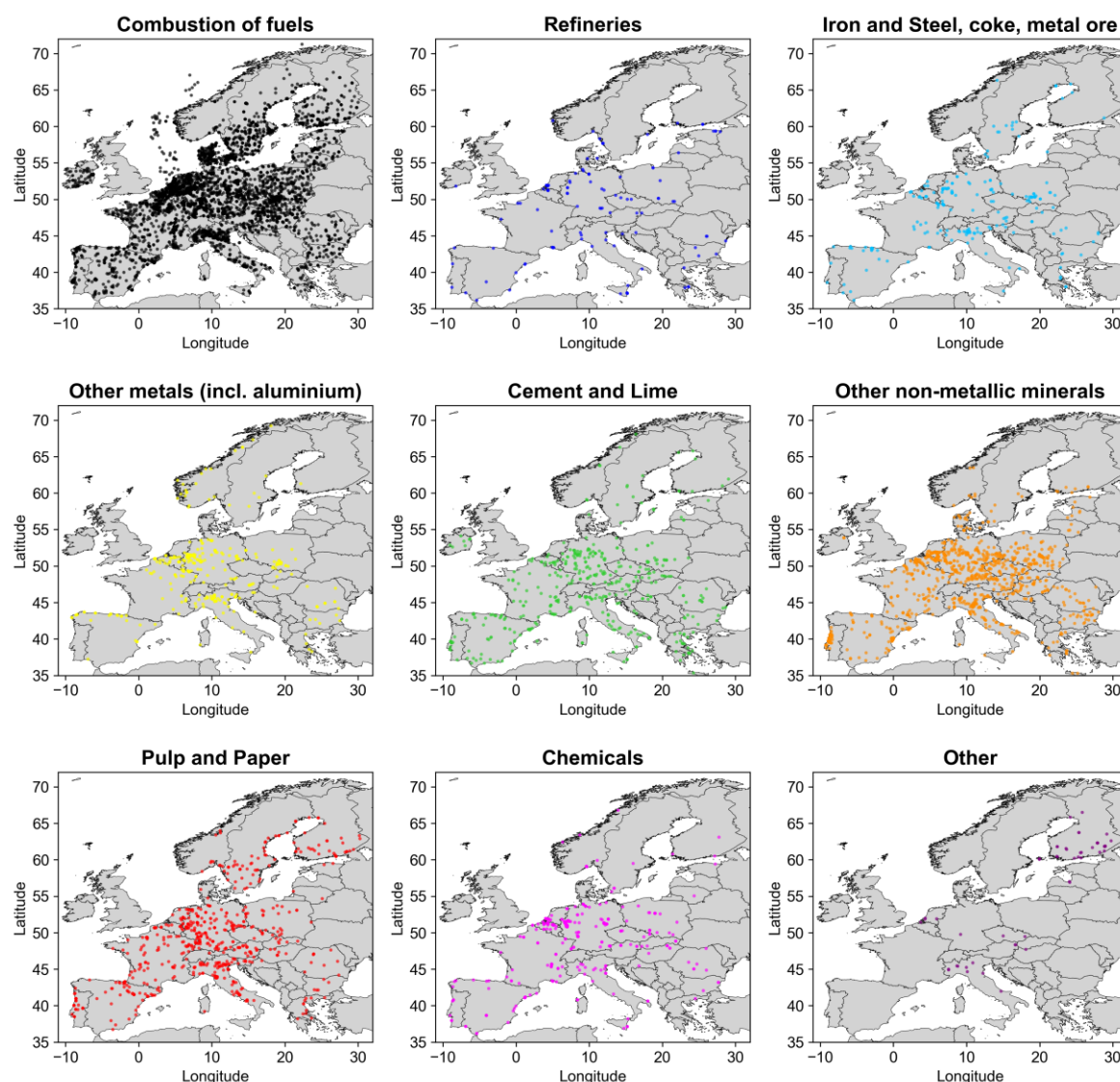


Figure 2: Collected geolocations of all stationary emitters reported in the EUTL framework according to their respective main industrial sector (EU ETS, 2024).

2.1.1 Selection criteria

Two specific criteria have been set for applying CEEGS technology within the scope of the project. Focused on the contribution to the reduction of CO₂ emitted to the atmosphere, a minimum amount of CO₂ coming from specific hard-to-abate industries has been considered. Such industries are mainly iron, steel, chemical and petrochemical production (IRENA, 2024). A more detailed list of sectors is provided by (DOE, 2024) as a part of their plan for large scale CCS deployment, which includes: Cement, Refining and Petrochemicals, Ammonia, Iron/Steel, Aluminium, Glass, Lime, Pulp and Paper, Soda Ash, and Liquefied Natural Gas (LNG).

The collected emission data is screened with respect to the amount of emitted CO₂ and the related industrial activities as well as the general sectors of its industrial application. Hard-to-abate sectors/activities are characterized by CO₂ emissions, which are integral to the involved processes, feedstock chains as well as product and/or by-product outputs. These industrial sectors are usually characterized by a high energy demand, strong growth and a projected increase in product demand in the upcoming decades, further complicating measures for emission reductions within an already challenging application framework for CCS/CCU/CCUS technologies. Despite the described general situation of hard-to-abate industries, slight improvements with respect to energy demand and CO₂

emission quantity can be expected in the upcoming decades. However, the conducted studies include all hard-to-abate emitters participating in the ETS and reported in the EUTL database, such as:

- Refineries/refining of mineral oil,
- Production of iron, steel and coke; processing of metal ore,
- Production/processing of other metals (aluminium, ferrous/non-ferrous metals),
- Production of cement and lime,
- Processing/production of other non-metallic minerals,
- Production of pulp and paper and
- Production of chemicals.

A detailed list of the aforementioned sectors and their related main activities, alongside the emission data of the entire EU-ETS of the year 2022, is given as additional information in Table 3. A correspondence can be established between these sectors and the activity of each installation. Activities used in EUTL is based on the NACE classification for economic activities (Regulation 1893/2006, Regulation 223/137) and adapted to the EUTL codes.

Table 3: Hard-to-abate sectors, relevant main activities and related emissions or 2022 (EU-wide) that have been assessed in this study.

Sector	Main activity	Activity code (NACE/EUTL)	Number of entities (-)	Verified emissions (Mt)
Refineries	Refining of mineral oil	21	108	109.19
Iron and Steel, coke, metal ore	Production of coke	22	15	5.40
	Metal ore roasting or sintering	23	10	2.02
	Production of pig iron or steel	24	179	95.30
Other metals (incl. aluminium)	Production or processing of ferrous metals	25	200	9.69
	Production of primary aluminium	26	28	6.78
	Production of secondary aluminium	27	26	1.13
	Production or processing of non-ferrous metals	28	75	6.41
Cement and Lime	Production of cement clinker ^a	29	207	104.64
	Production of lime, or calcination of dolomite/magnesite ^a	30	199	25.30
Other non-metallic minerals	Manufacture of glass ^b	31	297	16.64
	Manufacture of ceramics ^c	32	620	12.22
	Manufacture of mineral wool	33	43	1.79
	Production or processing of gypsum or plasterboard	34	35	1.03
Pulp and Paper	Production of pulp ^d	35	164	5.15
	Production of paper or cardboard ^d	36	422	15.93
Chemicals	Production of carbon black	37	17	1.52
	Production of nitric acid	38	25	2.34
	Production of adipic acid	39	2	0.10
	Production of glyoxal and glyoxylic acid	40	0	0.00
	Production of ammonia	41	18	12.57
	Production of bulk chemicals	42	244	29.36
	Production of hydrogen and synthesis gas	43	35	6.09
	Production of soda ash and sodium bicarbonate	44	11	4.28
Sum of all stationary installations			2980	474.89

^a some entities still used old ETS activity codes (e.g. "6 - Installations for the production of cement clinker in rotary kilns or lime in rotary kilns or in other furnaces") and therefore the linked reported and verified emissions might be incorrect;

^b including production of glass fibre;

^c includes all installations for the "manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain";

^d some entities still used old ETS activity codes (e.g. "9 - Industrial plants for the production of (a) pulp from timber or other fibrous materials (b) paper and board") and therefore the linked reported and verified emissions might be incorrect.

The verified amount of CO₂ emitted per facility or installation varies from 0 (not declared) to several millions of tons. The obligation to declare pollutants depends on criteria, such as economic activity, capacity threshold and emission threshold (Regulation 166/2006). In the case of the emission of CO₂ into the air, the threshold is established in 100 million kg/year. Facilities or installations with less than this amount can be present in the database for been considered in Annex I (Activities) of the

aforementioned regulation. For carrying out the analysis, a cut-off limit for individual CO₂ emissions has to be included to aid regional clustering and focus on large emitters, which can be part of a viable CO₂ transport network (rail/road/pipeline) in the future. After reviewing the range of values and activities, an annual emission threshold of 50 million kg/year was chosen.

2.1.2 Spatial emitter clustering

Given the applied selection criteria described in the previous section, the collected geolocations of all considered and relevant CO₂ emitters are required to be sorted into regional clusters. Through the identification of regional emitter clusters, synergies between close-by emitters with respect to transport infrastructure (CO₂ transport vectors, general accessibility, etc.), energy demand (heat integration, CO₂ separation and transport, etc.) and ultimately economic and lifecycle costs can be made available and amplified. Apart from that, potential CEEGS deployment sites and hence suitable underground storage locations can be put into a meaningful and cost-efficient spatial relation to large-volume, hard-to-abate emitters from the selected industrial sectors and activities.

The spatial emitter clusters presented in this study have been retrieved based on the data-clustering algorithm DBSCAN (density-based spatial clustering of applications with noise). DBSCAN is a non-parametric density-based clustering algorithm, which groups sets of points in a defined space. It is able to group points that are closely packed together (high-density areas, points with many nearby neighbours) and mark outlying points (low-density regions, nearest neighbours are too far away), which are treated as noise. In contrast to the more classical K-means clustering (spherical clusters without noise detection and required a-priori knowledge of the initial locations of cluster centroids), DBSCAN is able sufficiently cluster a large number of points into irregularly shaped clusters solely based on density without a-priori knowledge of the cluster centroids. The basic mechanisms and parameters of the DBSCAN algorithm are briefly introduced subsequently.

The basic idea behind the DBSCAN algorithm is the density-relation (or “density-connectedness”) of objects. Two objects are density-related, if a chain of dense objects (so-called “core points”, with more neighbours than *minPts*), connecting these two points, exists. The objects connected by the core points form a cluster, whereas objects not being part of this cluster are considered as noise points or noise cluster. DBSCAN features three different kinds of points:

- core points (which are dense by definition),
- (directly-) reachable points and
- outliers (not dense, not density-reachable).

The algorithm is characterized by two core parameters:

- ϵ (radius of a neighbourhood with respect to some point) and
- *minPts* (defines if an object is a core point, if it has at least *minPts* ϵ -reachable neighbours).

A basic schematic representation of the DBSCAN clustering algorithm is depicted in Figure 3 below.

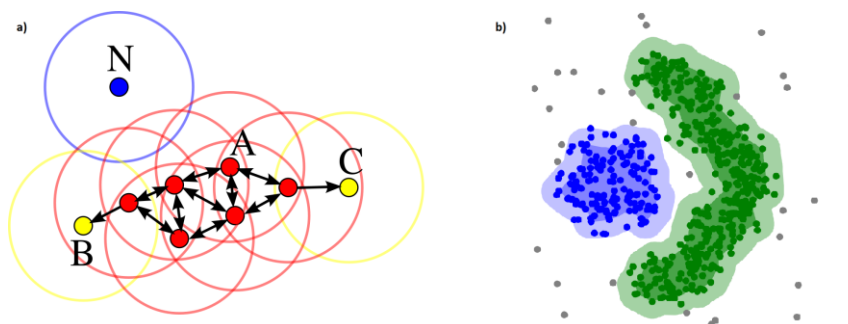


Figure 3: a) Schematic of the DBSCAN clustering algorithm for *minPts* of 4 (Chire, 2011) and b) non-linear/non-spherical clusters with noise from DBSCAN (Chire, 2011).

In Figure 3, *minPts* is set to 4. Point A and all other red points are core points, since the area surrounding these points lies within ϵ and contains at least 4 points, including the point itself. All of these points are reachable from one of each other, representing a single cluster. In contrast, points B and C are not considered as core points, while still being reachable from point A via other core points. Thus, points B and C also belong to the already identified cluster. The outlying point N is a noise point, as it neither represents a core point nor a directly-reachable point. However, reachability is not a symmetric relation leading to the fact that only core points are able to reach non-core points. A non-core point may be reachable, but no further points can be from them. This means, that a further notion (“connectedness”) is required to formally define the extent of the identified clusters. Two hypothetical points p and q are density-connected if they are both reachable from another point o . The notion of density connectedness is symmetric. Points within DBSCAN-identified cluster are mutually density-connected. Points are part of the cluster if they are density-reachable from some point of the DBSCAN cluster.

The following steps are part of the DBSCAN algorithm:

1. search for points within the ϵ -neighbourhood of every point and identification of all core points with a neighbour count exceeding *minPts*,
2. finding the connected core points on the neighbour graph (non-core points are ignored),
3. assignment of non-core points to either a nearby cluster (ϵ -neighbourhood) or to the noise (-cluster).

The main advantages of the DBSCAN algorithm with respect to the application framework of this study are:

- it requires no a-priori knowledge of the number of clusters and their initial centroid location,
- it can find clusters which are arbitrarily shaped (particularly useful for the identification of industrial emitter cluster with respect to transport/pipeline networks),
- it is robust to noise and returns an outlier/noise cluster (e.g. isolated emitters),
- it only requires two parameters (ϵ and *minPts*), which can be set by a domain expert if the used dataset is well understood.

The DBSCAN clustering parameters for the regional cases of Germany and Spain are chosen according to Table 4.

Table 4: Employed DBSCAN clustering parameters.

Parameter	Germany	Spain
ϵ	0.6 ^a	0.8 ^a
<i>minPts</i>	9	6

^a based on latitude/longitude data with projection WGS 84 (EPSG 4326)

The clustering of the collected industrial emitters for the cases of Germany and Spain is presented in Section 3. The clustering and all accompanying numerical operations were carried within Python 3.12 (Spyder) based on the machine learning add-on “scikit-learn”.

2.2 Geological storage sites

Previous EU projects have studied the subsurface for geothermal energy and gas storage. Efforts have been made to locate geological formations suitable for each purpose and the results are compiled in public databases like CO2StoP, ESTMAP, Hystories and GSEU. Data was also provided by national level projects like ALGECO2 in Spain or TUNB (TUNB, 2022) and CO2STORE in Germany as well as established federal databases like the Speicher-Kataster of the BGR (Federal Institute for Geosciences and Natural Resources of Germany). Data sources for Spain have been extracted from ALGECO2 and Hystories projects. A first screening has been done to include only onshore storage sites. They are deep saline aquifers (DSA) in sandstones and carbonates. Information of saline formations suitable for storage in cavities has been taken from previous research conducted by CSIC (González-Esvertit, E. et al., 2022).

2.2.1 Geological sites for Germany

Germany has significant potential for CO₂ storage in deep geological formations. The main suitable storage options are:

1. Deep saline aquifers, which are porous rock formations filled with saltwater, primarily located in the North German Basin and offshore areas of the North Sea. They offer large-scale storage potential of about 9 Gt (Knopf, 2010).
2. Depleted gas and oil fields, located also in northern Germany and offshore, and provide additional storage potential of about 2.75 Gt (Knopf, 2010).

In a current national research project, the storage sites of the TUNB data base (TUNB, 2022) have been investigated according an analytical hierarchy process (AHP) to score and rank the available sites (Xu, 2024 (submitted)). In order to predict the storage potential of renewable energies in salt formations, such as salt domes and salt diapirs, their distribution has been assessed for planning and provisioning salt caverns for future energy storage (InSpEE, 2015; InSpEE-DS, 2020).

2.2.1.1 Deep saline aquifers (DSA)

Germany possesses numerous sedimentary basins suitable for deep saline aquifer (DSA) CO₂ storage, primarily the North German Basin (NGB), the Upper Rhine Graben (URG), and the South German Molasse Basin (SMB). The North German Basin features thick Permian to Tertiary sediments. Key storage targets are the Buntsandstein (Triassic sandstone) and Rotliegend (Permian sandstone) formations, which have favorable porosity (> 15 %) and permeability (10 to 1,000 mD). These formations are overlain by caprocks of anhydrite or halite, providing effective sealing. The Rotliegend sandstones, at depths between 2,500 and 4,000 meters, are particularly suitable for CO₂ storage. The TUNB project has enhanced understanding of the NGB's subsurface geology, resulting in comprehensive 3D geological models using data from maps, wells, and seismic surveys. The Upper Rhine Graben offers storage opportunities in Mesozoic and Cenozoic sediments, including Triassic Buntsandstein and Jurassic formations. Its geothermal gradient makes it suitable for enhanced geothermal systems, combining geothermal energy with CO₂ storage. Potential storage formations are at depths between 1,500 and 3,500 meters. The South German Molasse Basin contains thick Tertiary sedimentary sequences, with storage potential primarily in deep aquifers like the Upper Jurassic Malm carbonates at depths greater than 800 meters. The 3DGEO-EU project focussed on homogenizing 3D geological models across borders, addressing challenges such as differing stratigraphic definitions and heterogeneous data (3DGEO-EU, 2021).

2.2.1.2 Salt formations

Germany's long history of salt extraction provides a unique opportunity for CO₂ storage in salt caverns. The main salt formations considered for CO₂ storage include the Zechstein and Upper Permian deposits, widespread throughout the North German Basin. The Zechstein salt formations have

significant potential due to their thickness, structural integrity, and widespread occurrence, offering possibilities for salt cavern development for CO₂ storage. The Zechstein salt is typically more than 200 meters thick, and salt diapirs are well-documented, particularly in the North German Basin. These salt structures have been extensively characterized by both the mining industry and geological surveys, providing detailed knowledge of their geometry and mechanical properties. The Geological Survey of Lower Saxony (LBEG) has compiled data on the location, depth, and thickness of these salt deposits for evaluating their suitability for CO₂ storage (Zhang, 2013).

2.2.1.3 Depleted oil and gas fields

A key depleted gas field is the Altmark gas field, one of Europe's largest onshore gas fields. Located in Saxony-Anhalt, the Altmark field has been considered for CO₂-enhanced gas recovery (EGR) and storage. Studies show that the field's Rotliegend sandstones, at depths around 3,000 meters, have suitable porosity and permeability for CO₂ storage (BGR, 2011).

Depleted oil fields, such as those in the Lower Saxony Basin (e.g., Emlichheim and Mittelplate fields), have also been evaluated for storage capacity. However, their relatively small size and complex geology may limit their CO₂ storage potential compared to saline aquifers and gas fields. Data on these depleted fields have been compiled by BGR and are included in the German CO₂ Storage Atlas, providing detailed information on reservoir properties, seal integrity, and estimated storage capacities (BGR, 2011).

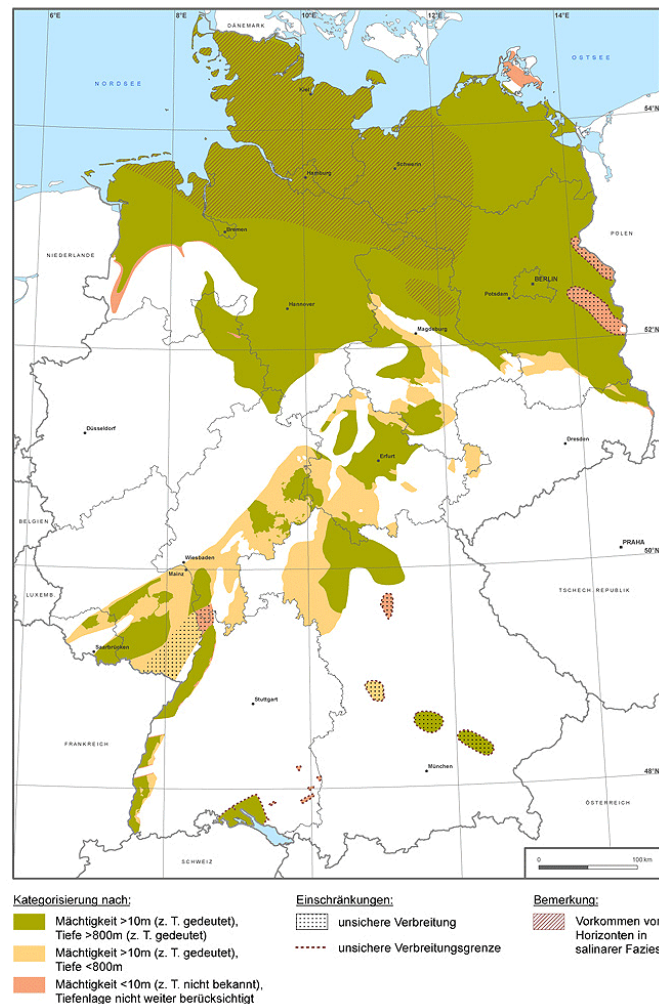


Figure 4: Nation-wide thematic map - deposits of the Permo-Carboniferous as potential reservoir rock unit with categorization based on depth and thickness (BGR, 2011).

2.2.2 Geological sites for Spain

At present, potential storage sites in Spain are still being studied. Two types of sites are being considered, deep saline aquifers (DSA) and salt formations.

2.2.2.1 Deep saline aquifers (DSA)

Spain, as part of the Iberian Peninsula, has four main geological domains related to potential formations for DSA geological storage are (Figure 5) Cantabrian Range and Duero Basin (CD); Pyrenees and Ebro Basin (PE); Iberian Range, and Tajo and Almazán Basins (IT); and Betic Cordillera and Guadalquivir Basin (BG).

The highest potential for geological storage is in Triassic (Buntsandstein Facies) and Jurassic deposits formed by Lias, Dogger and Malm series, but also storage potential has been identified in Cretaceous formation (Utrillas and Carbonates formations). In the Guadalquivir basin, Guadalquivir Sands Formation (Tortonian-Messinian, Neogene) are relevant due to high presence of gas commercial accumulations.

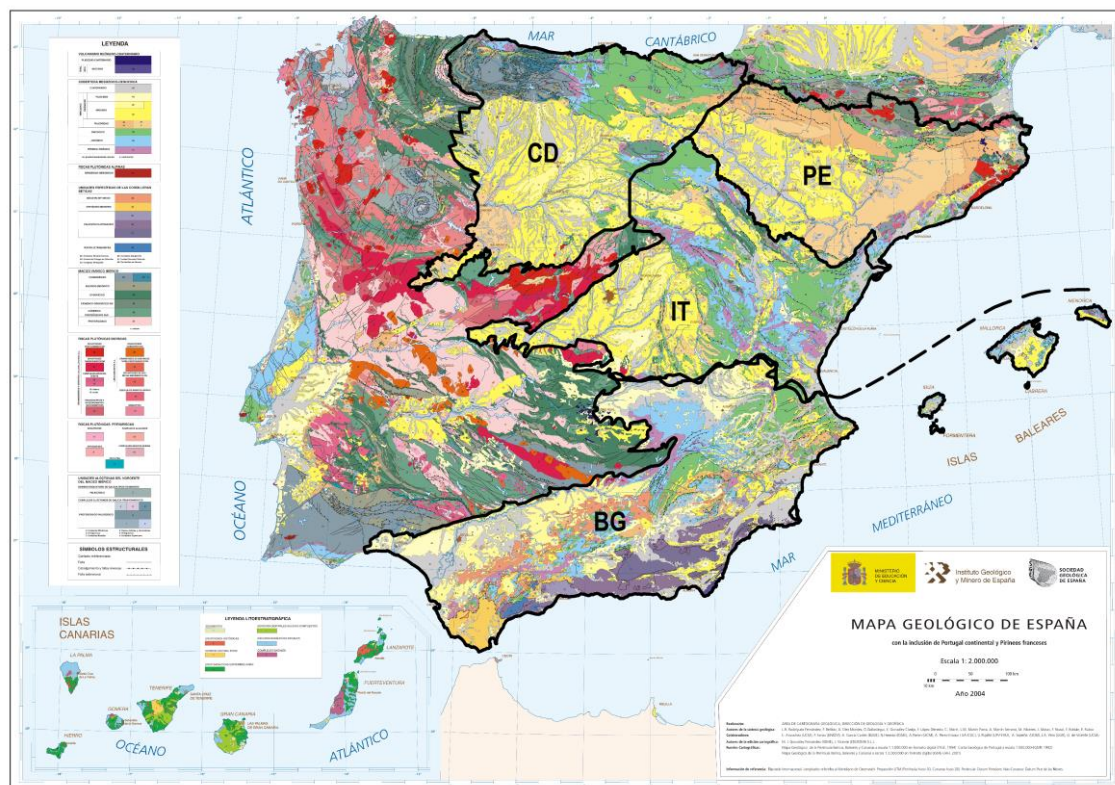


Figure 5: Overview of Spanish geological domains with potential for geological storage. ALGECO2 project. Base map from (IGME, 2004). Cantabrian Range and Duero Basin (CD); Pyrenees and Ebro Basin (PE); Iberian Range, and Tajo and Almazán Basins (IT); and Betic Cordillera and Guadalquivir Basin (BG).

The Triassic Sedimentary basins have sequences that generally range from the Triassic to the Neogene, with depths exceeding 3,000 m. The main potential is identified in saline aquifers. There are also identified onshore and offshore oil and gas fields in the Guadalquivir basin (gas), Ebro basin (oil and gas), and Cantabrian Range and Duero Basin (oil and gas).

The main source of data considered is the ALGECO2 project, carried out by the IGME in 2010 with the objective of identifying geological structures with potential for CO₂ storage. A great effort was made to collect existing information of subsurface and its reinterpretation following the guidelines of the transposition of Directive 2009/31/CE on the CO₂ storage law approved by Law 40/2010 of 29th

December, digitalization of the documentation, and evaluation and classification of 103 identified structures based on expert criteria. The project was focused on saline aquifers of the main onshore sedimentary basins.

This information was updated with CO2StoP and ESTMAP projects. The new information, mainly number and extent of reservoir formations and geological unit definition, comes from new reviews of existing data and new data from in-house projects.

The GIS layers include the Storage Units polygons, grouping the favourable structures, and the Traps polygons from previously defined structures Figure 19 a). Delimitation has been done from isobath maps of the tops, considering a minimum depth of 800 m, of formations from previous studies carried out by the IGME.

Traps layer includes four active gas stores in Spain. The basic gas storage data was provided by ENAGAS (national operator of gas infrastructure), and completed from literature, national hydrocarbons database (www.minetur.gob.es, Archivo Técnico de Hidrocarburos) or statistics (www.cores.es). This database includes properties of the formations like depths, temperatures, permeabilities and porosities. The access to all data is open and no confidential data is included.

2.2.2.2 Salt formations

CO₂ storage in salt formations has not been well studied in Spain. However, recent compilation has been made by (González-Esvertit, E. et al., 2022). The results of this work are compiled in the Iberian Evaporite Structure Database (IESDB), sourcing from six different databases and more than 1,500 published and unpublished references, and includes information and figures for each of the 150 inventoried evaporite structures and their surrounding rocks. The database targets outcropping and buried diapirs, undeformed to slightly deformed evaporite successions, evaporite-cored anticlines, evaporite-detached thrusts, and allochthonous evaporite bodies. Compiled data includes information about the stratigraphy, structure, event chronology, subsurface data availability, mining activity, and key bibliographic references of each indexed structure. The IESDB follows the FAIR principles of database management (Findable, Accessible, Interoperable and Reusable) and is presented as an open access webpage (<https://iesdb.eu/>).

A map with the larger salt outcrops can be presented here, with areas where further investigations can be carried out in order to locate the most suitable places for building cavities.

2.2.3 Selection criteria

Among the suitable storage locations contained in the data catalogue, a screening must be carried out to choose those that present characteristics that respond to some specific criteria of the CEEGS technology. These criteria refer to the main constraints that could affect the performance of the system, such as minimum pressure conditions to ensure CO₂ supercritical state, range of porosity and permeability which influence the development of the setting of the initial plume, etc. (Alcalde et al., 2021), (Bachu, 2003), (Putriyana et al., 2023), (Callas et al., 2022), (IEA, 2009), (Anthonsen, 2014), (IGME, 2010). Such a screening method has been proven for CO₂-based geothermal concepts (Uliasz-Misiak, 2021).

For that purpose, a detailed compilation of criteria was made in the scope of the CEEGS project and was reported in deliverable D2.4. Two types of criteria were defined for deep saline aquifers, 9 mandatory (exclusionary) grouped in 4 classes (Table 5) and 10 prioritisation criteria (Table 6). For salt cavities 5 prioritization criteria grouped into 3 classes were used (Table 7). It is recommended to use the specific Excel spreadsheet “Screening and Ranking Tool” to facilitate the selection and ranking of the storage sites for the scenario definition. For more detailed information see D2.4. The application of some of the criteria may be not considered depending on the results of the scenario definition at this stage. Also, additional criteria could be considered as more data and knowledge is incorporated.

Table 5: Mandatory criteria for DSA CO₂ storage site selection, from D2.4.

		Criteria	Data
Mandatory criteria (safe CO ₂ storage according to technology and legal requirements)	Storage site definition	DEPTH of storage formation	> 1300 m
		SEAL thickness	> 50 m
		BRINE salinity	> 10000 ppm TSD
	Storage site Lithology	% CLAY (mass)	< 30 %
	Petrophysical properties	Absolute Porosity (intergranular)	< 15 %
		Seal permeability	< 0.02 mD
	Risks (complex area) (identified or expected)	Open Faults	NO
		Active faults	NO
		Orphan wells	NO

Table 6: Prioritization criteria for DSA CO₂ storage site selection, from D2.4.

		Criteria	Data
Prioritization criteria Focus on priorities: (1) Q storage (2) CO ₂ storage (3) Q recovery	Storage site definition	Structure closure	Closed
		Thickness	10 – 100 m
		Brine salinity	> 100000 ppm TDS
	Lithology	Homogeneity and lateral continuity	Homogeneous
	Petrophysical properties	Permeability	10 – 1000 mD
		Absolute Porosity	10 – 15 %
	Geomechanical properties	Fractures networks	Null/low
	Thermal properties	Heat Flow Density	> 70 mW/m ²
		Rock thermal capacity	> 800 J/(kg K)
	Complex Area Features	Natural seismicity	Low/null

Table 7: Prioritization criteria for CO₂ storage site selection in salt cavities, from D2.4.

		Criteria	Data
Prioritization criteria for salt cavities	Storage site definition	Type of formation	Dome
		Thickness	> 100 m
		Depth of storage formation	800 – 1700 m
	Thermal properties	Geothermal gradient	> 33 °C/km
	Petrophysical properties	Halite content	> 95 %

3 Scenarios definition

Scenarios definition is based on previous experiences on CCS cluster projects in Europe (e.g. STRATEGY CCUS, 2022). The methodology is aimed to answer three questions: what CO₂ will be captured; how will this be captured, collected and transported; and where will it be stored. The concept of industrial CCS clusters is based on the efficiencies that may arise from shared use of infrastructure, expertise and resources when a number of CO₂ capture facilities are linked within an industrial area, leading to lower costs for the reduction of emissions. This approach focuses on the characterisation of features like emissions, area, industries, relationships, infrastructure and CO₂ storage.

As first version report, this document outlines where the most important regions in terms of emissions and storage potential can be found. As a result, the outcome will be a first proposal with possible regions by country with clusters and storage sites to consider. They will be the result of the application of criteria selection for both emitters and storage sites.

The starting point is the cartographic representation of the emission sources and the clustering by emitter locational density. The overlap of the storage sites gives a first impression of how both features are spatially related. Further considerations will be used in the final version to refine search and select representative scenarios for applying CEEGS, including for example means of transportation, energy consumption, pollutants, use, etc. Guidelines will be given in the recommendations section.

3.1 Germany region

3.1.1 Emitters

The EUTL database of Germany for the year 2022 contains 1611 stationary emitting installations, of which 1573 reported total verified CO₂ emissions amounting to 336.83 Mt. Over 67 % of the verified CO₂ emission reported for Germany can be allocated to the combustion of fuels, leading to total annual CO₂ emissions from hard-to-abate industrial sectors of 110.02 Mt from 732 industrial installations scattered across the country. The 732 hard-to-abate industrial CO₂ emitters are ranging from a maximum emission of 7.94 Mt to 1 t per year.

Considering only emissions larger than 50kt/year, results in 274 industrial installations with total annual CO₂ emissions of 102.18Mt. All reporting emitters for Germany abiding to the chosen emission threshold are compiled in Table 8, alongside their respective industrial activity, number of entities, verified CO₂ emissions and emission share. Based on the aforementioned emission statistics and the chosen emission threshold (50 kt/year) it becomes evident, that large-scale emitters dominate the overall CO₂ emissions of hard-to-abate industries in Germany despite the fewer number of installations (274 entities).

Table 8: Data of hard-to-abate CO₂ emissions in Germany for year 2022 summarized by industrial activity for selected emitters greater than 50 kt/year.

Main activity	Activity code (NACE/EUTL)	Number of entities (-)	Verified emissions (Mt)	Emitted CO ₂ (%)
Refining of mineral oil	21	18	22.24	21.76
Production of coke	22	4	3.77	3.69
Metal ore roasting or sintering	23	1	0.06	0.06
Production of pig iron or steel	24	22	25.88	25.33
Production or processing of ferrous metals	25	18	1.59	1.56
Production of primary aluminium	26	5	0.88	0.86
Production of secondary aluminium	27	2	0.36	0.35
Production or processing of non-ferrous metals	28	6	0.67	0.65
Production of cement clinker ^a	29	35	18.76	18.36
Production of lime, or calcination of dolomite/magnesite ^a	30	46	8.41	8.23
Manufacture of glass ^b	31	30	2.81	2.75
Manufacture of ceramics ^c	32	2	0.11	0.11
Manufacture of mineral wool	33	4	0.32	0.32
Production or processing of gypsum or plasterboard	34	1	0.07	0.06
Production of pulp ^d	35	3	0.26	0.25
Production of paper or cardboard ^d	36	29	3.24	3.17
Production of carbon black	37	2	0.52	0.51
Production of nitric acid	38	2	0.27	0.26
Production of adipic acid	39	1	0.08	0.08
Production of glyoxal and glyoxylic acid	40	0	0.00	0.00
Production of ammonia	41	5	3.14	3.07
Production of bulk chemicals	42	27	6.15	6.02
Production of hydrogen and synthesis gas	43	8	2.14	2.10
Production of soda ash and sodium bicarbonate	44	3	0.45	0.44
Sum of all stationary installations		274	102.18	100

^a some entities still used old ETS activity codes (e.g. "6 - Installations for the production of cement clinker in rotary kilns or lime in rotary kilns or in other furnaces") and therefore the linked reported and verified emissions might be incorrect;

^b including production of glass fibre;

^c includes all installations for the "manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain";

^d some entities still used old ETS activity codes (e.g. "9 - Industrial plants for the production of (a) pulp from timber or other fibrous materials (b) paper and board") and therefore the linked reported and verified emissions might be incorrect.

Most of the emissions are related to the production of pig iron or steel and refining of mineral oil, accounting for 47.09 % of the hard-to-abate CO₂ emissions, and reaching 48.12 Mt for a total 40 installations. These industrial activities are followed by the production of cement clinker with total CO₂

emissions of 18.76 Mt (18.36 %) from 35 emitting installations, and the production of lime, or calcination of dolomite/magnesite with 8.41 Mt (8.23 %) from 46 emitting installations. The production of bulk chemicals is characterized by total CO₂ emissions of 6.15 Mt (6.02 %) from 27 reporting emitters. The remaining 20.3% of the industrial emitters (126 installations) sum up 20.74 Mt, which individually represent less than 5 % of the total reported amount each. The geographical distribution of the emitters according to their main industrial sector and annual emission quantity is shown in Figure 6.

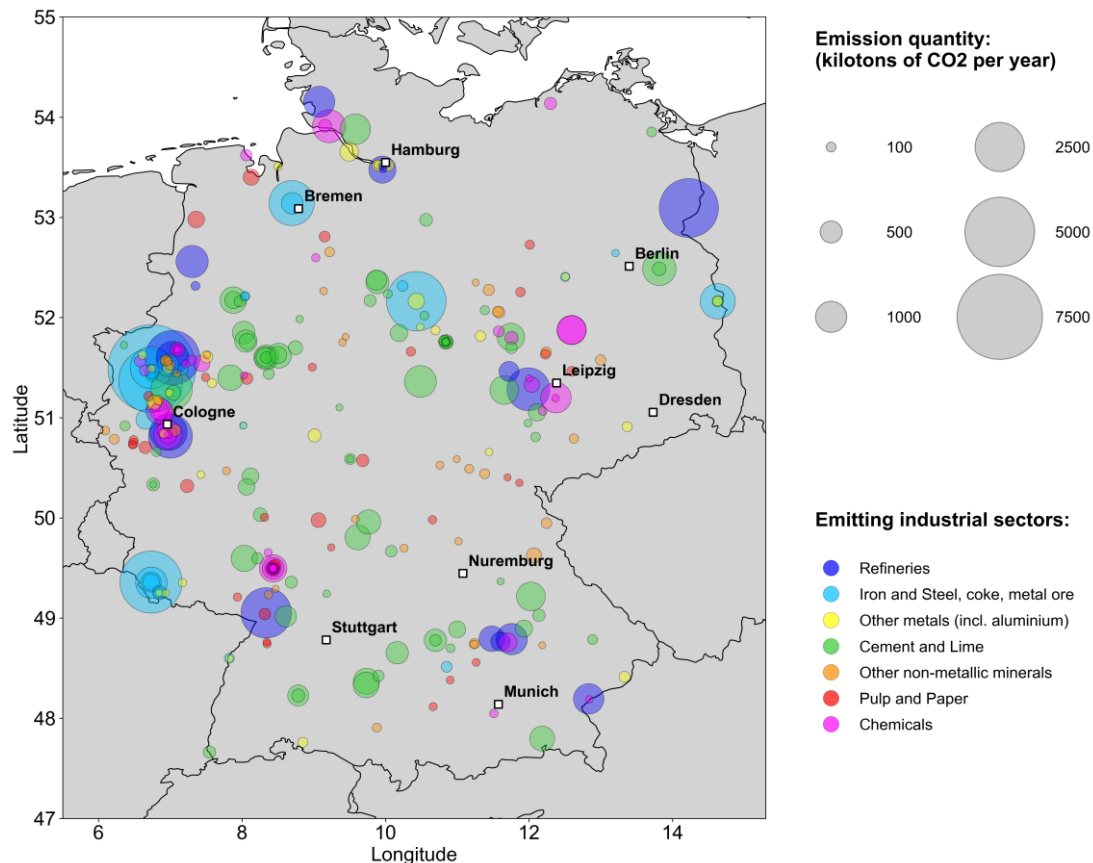


Figure 6: Location and emission quantity (in kilotons) of hard-to-abate emitters grouped by industrial sectors for Germany and the year 2022.

Although the majority of industrial emitters from hard-to-abate sectors is more or less uniformly scattered across the country, there are specific regional emitter conglomerates, such as in North Rhine-Westphalia (close to Cologne), Northern Germany (Bremen and Hamburg), Northern Saxony/Saxony-Anhalt/Lower Saxony (from Leipzig to Hannover), Bavaria (between Munich and Nuremberg) as well as the Rhine-Main area (northwest of Stuttgart). Except for the numerous emitters in the area of Leipzig and Saxony-Anhalt, the emitter density in Eastern Germany is considerably lower when compared to the western part of the country. However, there are still large-scale emitters present, especially in the Berlin/Brandenburg region with the cement production plant in Rüdersdorf, the steel works in Frankfurt (Oder) and PCK refinery in Schwedt.

3.1.2 Storage sites

Relevant storage sites from DSA and salt structures for Germany are displayed in Figure 7. Porous storage units are predominantly found in the northern German basin as well as offshore in the North and Baltic Sea. Known geological traps of porous units from established and/or depleted oil and gas fields are also found in the northern part of Germany and to large parts in the Northern Sea. Despite the clear accumulation of porous storage space in the north of Germany, there are numerous other

potential storage regions throughout the country, such as in Thuringia & northern Bavaria, Rhineland-Palatinate, the upper Rhine valley as well as the southern edge of the country.

In contrast, potential storage sites featuring salt caverns would be exclusively situated in North Germany due to the isolated occurrence of suitable salt pillows and diapirs in the north German basin.

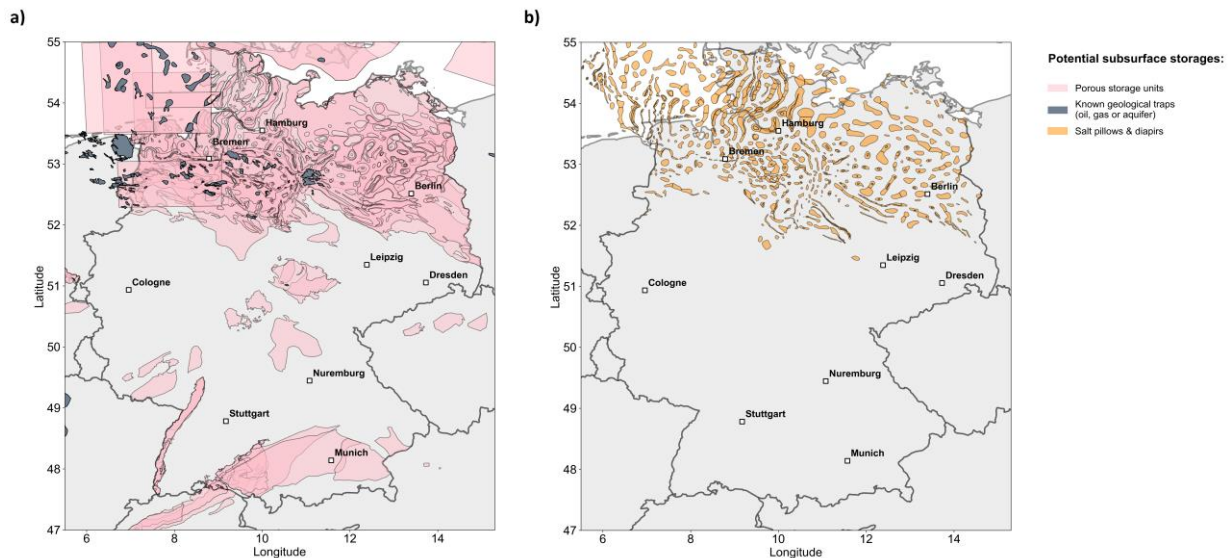


Figure 7: Potential CO₂ storage areas in Germany for a) DSA and known geological traps (depleted oil or gas fields and other aquifers) and b) onshore and offshore salt structures (salt pillows & diapirs).

However, the potential storage formations depicted in Figure 7 are not yet screened by the respective storage formation depth. This is crucial for the operation of the CEEGS system due to the requirement of CO₂ at supercritical state, which only can be ensured at sufficient storage depths and hence pressures. The depths of the identified DSA storage sites (Figure 7 a)) largely lie beneath 800 m and deeper. Nonetheless, further detailed depth screening will be required and conducted in preparation of the final version of this deliverable until the end of task T6.2.

3.1.3 Clustering and scenarios

Utilizing the DBSCAN clustering algorithm introduced in Section 2.1.2, a total of 6 emitter clusters was identified based on the national emission data of Germany, accompanied by a number of outliers (distant, isolated emitters). The identified outliers or noise points will be excluded from subsequent analyses. However, it might be worthwhile to include some of the isolated emitters into the identified clusters with respect to future transport network planning and analysis (pipelines, road and rail), as long as the specific emitter is large enough, thus leading to potential techno-economic incentives for later inclusion. The determined emitter clusters are displayed in Figure 8.

The largest emission cluster is cluster 2 (magenta bubbles) with an approximate emission quantity of 39.8 Mt CO₂ in the year 2022 emitted by 90 installations. Cluster 2 is mainly located in the historical industrial heartland of the Ruhr area in the federal state of North Rhine-Westphalia, predominantly north and around Cologne. Other large industrial emitter clusters were computed for the regions of central Bavaria (cluster 1 indicated by dark blue bubbles; between Munich and Nuremberg; approx. 6 Mt from 21 installations) and in Central/East Germany (cluster 4 indicated by light blue bubbles; between Leipzig and Hannover; approx. 17.3 Mt from 52 installations). Other smaller emitter clusters were determined around Hamburg (cluster 6 indicated by red bubbles; approx. 4.9 Mt; 11 installations), the Saarland (cluster 5 indicated by yellow bubbles; approx. 6.3 Mt; 9 installations) as well as between Karlsruhe and Frankfurt am Main (cluster 3 indicated by green bubbles; approx. 8.3 Mt; 31 installations).

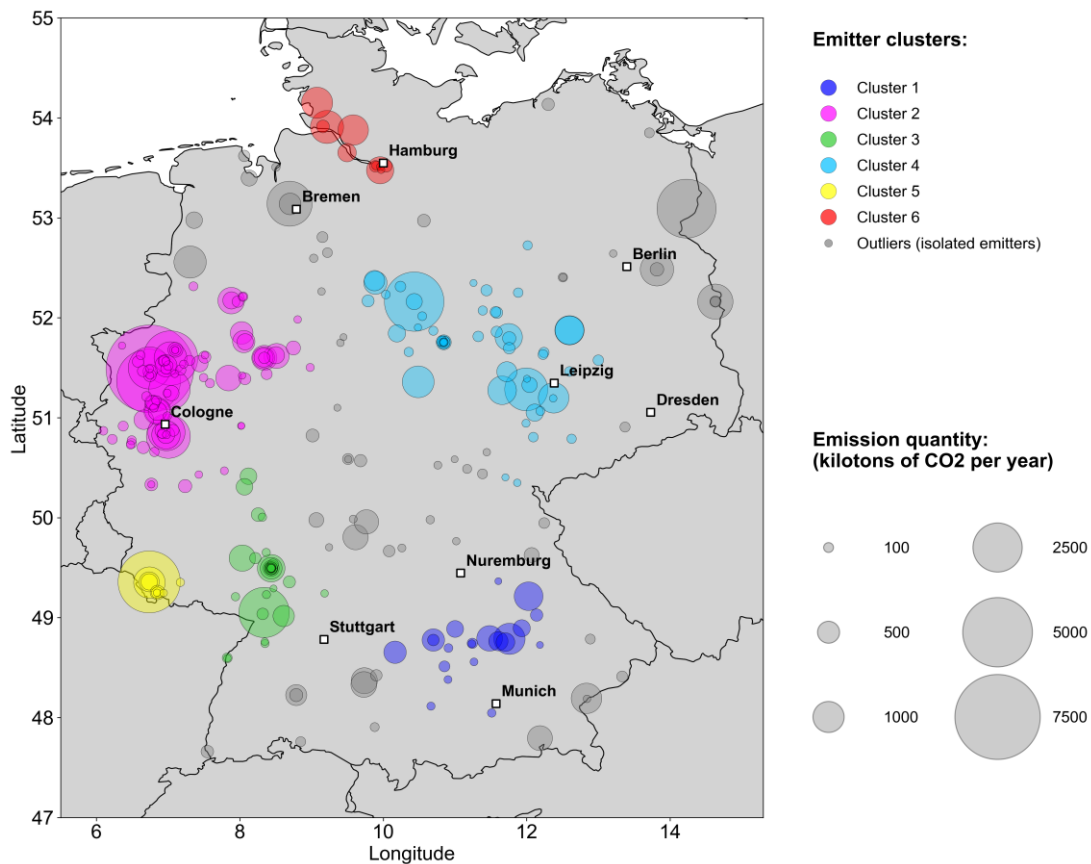


Figure 8: Location and emission quantity (in kilotons) of the identified emitter clusters (based on the DBSCAN algorithm) for Germany and the year 2022.

Given the predefined emission threshold of 50 kt/year, total considered CO₂ emissions approx. 82.5 Mt were determined for clusters 1 to 6 combined, comprising 214 single industrial installations. Outliers account for approx. 19.7 Mt CO₂ emissions originating from 60 isolated emitter locations. It has to be noted, that the applied DBSCAN methodology does not account for other relevant infrastructure in relation to the collected emitter locations. In other words, already existing transport infrastructure (pipelines, rail and road) might elevate some isolated emitter locations into the already identified emitter clusters as previously stated in the introductory paragraph of this section. A brief overview over existing transport infrastructure for Germany in relation to the locations of the emitter clusters will be given later. A detailed summary of the presented emitter clusters for Germany with respect to their industrial sectors, main activities, installation numbers and ultimately emissions quantity is tabulated in Table 10.

An overlap of the regions of potential DSA storage in Germany with the locations and quantities of the previously identified emitter clusters is shown in Figure 9. As already outlined in Section 3.1.2, potential DSA storage sites will be most likely situated in North Germany due to the widespread presence of suitable storage units. Potential storage spaces outside the northern part of the country are found in the central (Thuringia) and southern/south-western (Alpine foreland, Rhine valley, etc.) part of Germany. Due to their vicinity to potential DSA storage areas, emitter clusters 1, 3, 4, 5 and 6 are identified as most beneficial study locations and hence assessment conglomerates as they are supposed to be characterized by minimized CO₂ transport costs, potentially aiding CEEGS process economics.

Although cluster 2 and its largest single emitters will most likely be discarded prior to the final assessment due to its relative geographic isolation from DSA storage regions, single emitters of its north-eastern sub-cluster coincide with DSA locations. This means that this sub-cluster could be

included within a single regional assessment, if the overall emission quantity and complementary CO₂ network studies (transport pipeline layout based on minimum-cost heuristic methods, such as the node valency transfer metaheuristic as featured by Yeates et al.) indicate a beneficial economic framework (Yeates, 2021). However, extended network studies are not part of task 6.2 and this deliverable and will therefore be addressed in future research projects focussed on the CEEGS technology and its regional deployment.

Except for cluster 6, all remaining DSA-linked emitter clusters are at least composed of some single emitter sites with no direct access to DSA storage space. However, their relative vicinity to said DSA locations is considered to not negatively affect the overall economic performance of a hypothetical CEEGS storage system based on the current knowledge of the authors, as some means of CO₂ transport infrastructure and associated costs will always be included in the regional assessment cases. Isolated sites within the positively screened emitter clusters could also be excluded subsequently in future studies. A preliminary storage site/emitter cluster pair quality assessment based on the locational data shown in Figure 9 and Figure 10 is compiled in Table 9.

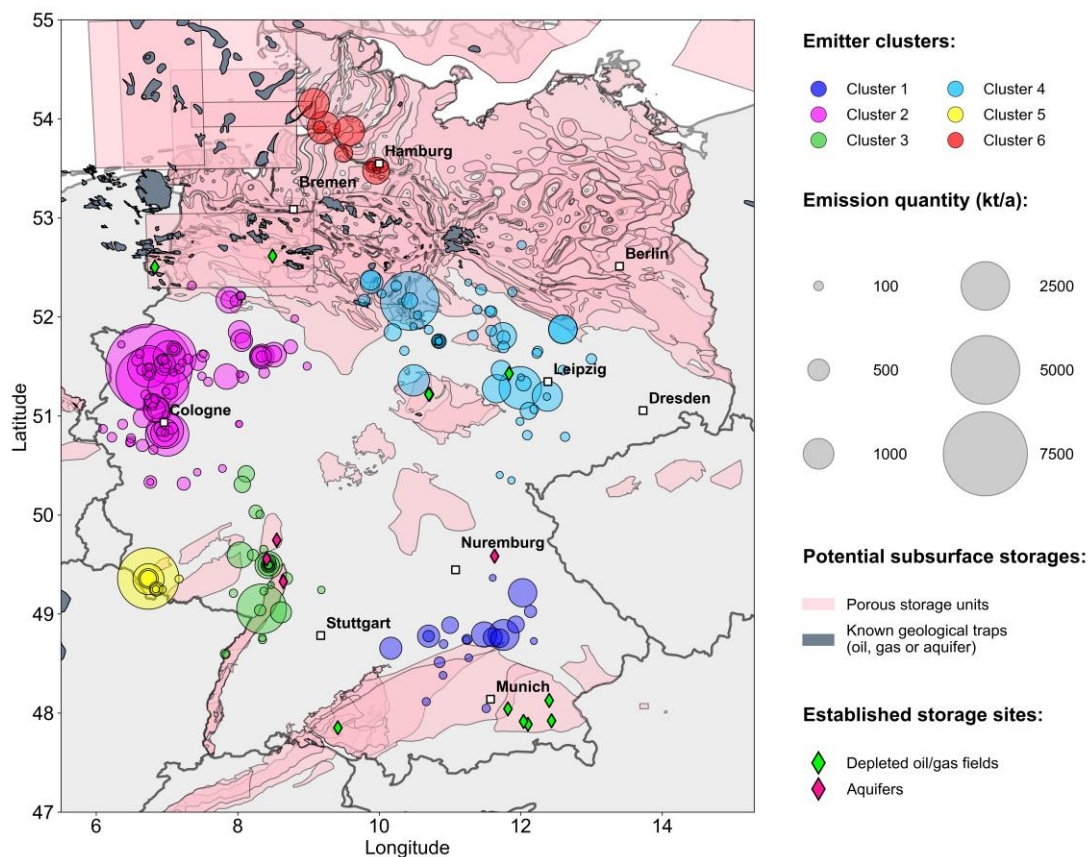


Figure 9: Location and emission quantity (in kilotons) of the identified emitter clusters in relation to potential DSA CO₂ storage sites for Germany.

An equivalent assessment was carried out for salt formations present in the northern German subsurface space. Figure 10 depicts salt pillows and salt diapirs in relation to the identified emitter clusters. It is evident that DSA formations in Northern Germany coincide with salt formations. The overlap reveals, that only cluster 6, cluster 4 (with some limitations regarding isolated emitters and hence transportation infrastructure required) and cluster 2 (with larger limitation regarding isolated emitters and hence transportation infrastructure required) can be potentially used within a salt-cavern-based setup. These clusters also feature already existing storage infrastructure, which would have to be re-purposed from NG to CO₂. Emitter clusters 1, 3 and 5 will not be considered within an assessment scenario employing salt formations as CO₂ storage formations.

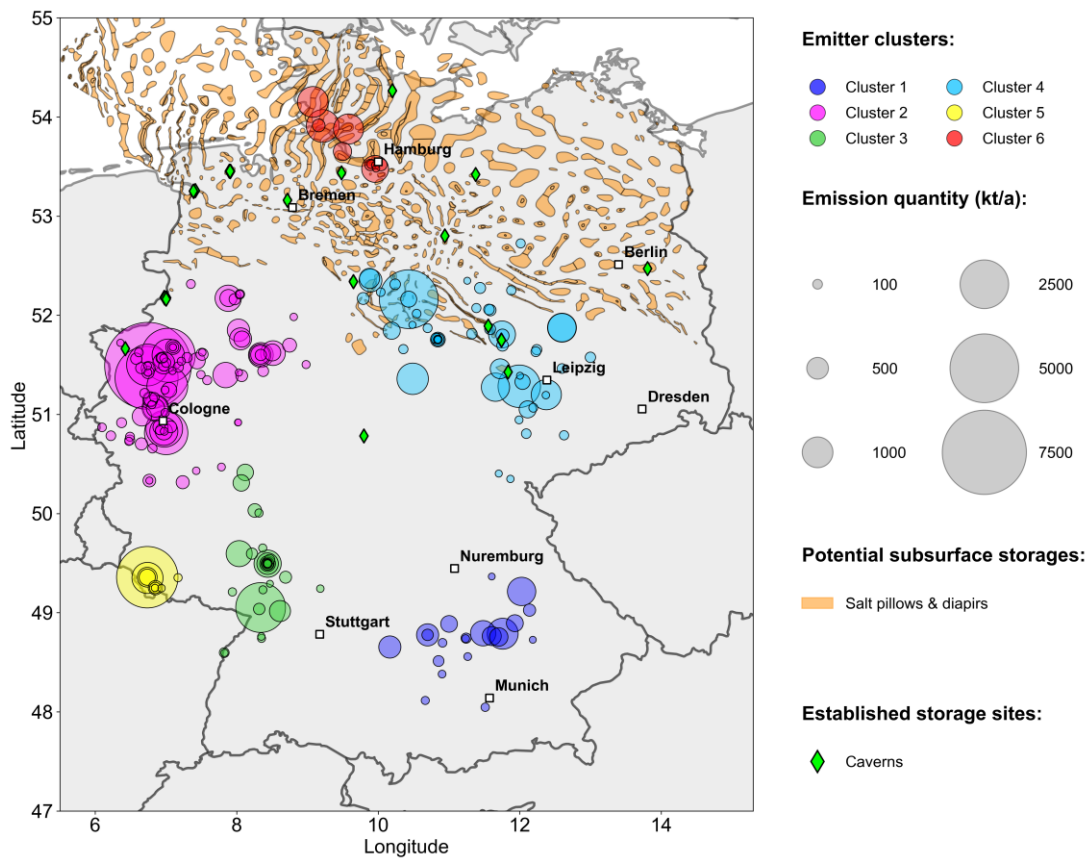


Figure 10: Location and emission quantity (in kilotons) of the identified emitter clusters in relation to potential CO₂ storage sites in salt formations for Germany.

The comparative and preliminary storage site/emitter cluster pair quality assessment is summarized Table 9.

Table 9: Preliminary comparative storage site and emitter cluster pair quality assessment.

Cluster	DSA storage units	Salt formation units
1	+	--
2	-	0
3	++	--
4	++	+
5	+	--
6	++	++

Table 10: Detailed emission data (only emitters with quantities 50 > kt CO₂ per year) of the retrieved emission clusters in Germany for 2022.

Sector	Main activity	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5		Cluster 6		Outliers	
		No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)
Refineries	Refining of mineral oil	3	2.08	5	7.69	1	2.62	2	2.33	-	-	4	1.89	3	5.63
Iron and Steel, coke, metal ore	Production of coke	-	-	3	2.75	-	-	-	-	1	1.02	-	-	-	-
	Metal ore roasting or sintering	-	-	1	0.06	-	-	-	-	-	-	-	-	-	-
	Production of pig iron or steel	1	0.12	8	12.83	1	0.10	2	3.77	5	5.04	-	-	5	4.02
Other metals (incl. aluminium)	Production or processing of ferrous metals	-	-	6	0.41	1	0.06	2	0.36	3	0.19	1	0.08	5	0.50
	Production of primary aluminium	-	-	3	0.39	-	-	-	-	-	-	2	0.49	-	-
	Production of secondary aluminium	-	-	1	0.24	-	-	1	0.12	-	-	-	-	-	-
	Production or processing of non-ferrous metals	-	-	1	0.15	-	-	1	0.06	-	-	1	0.15	3	0.30
Cement and Lime	Production of cement clinker	4	2.19	12	5.22	4	1.54	5	3.64	-	-	1	0.96	9	5.22
	Production of lime, or calcination of dolomite/magnesite	5	0.73	11	3.45	4	0.77	16	2.22	-	-	-	-	10	1.24
Other non-metallic minerals	Manufacture of glass	1	0.07	10	0.94	2	0.12	5	0.61	-	-	-	-	12	1.07
	Manufacture of ceramics	1	0.05	-	-	-	-	-	-	-	-	-	-	1	0.06
	Manufacture of mineral wool	1	0.11	1	0.07	-	-	2	0.14	-	-	-	-	-	-
	Production or processing of gypsum or plasterboard	-	-	-	-	-	-	-	-	-	-	-	-	1	0.07
Pulp and Paper	Production of pulp	-	-	-	-	1	0.12	2	0.14	-	-	-	-	-	-
	Production of paper or cardboard	3	0.20	9	0.99	5	0.41	5	0.45	-	-	-	-	7	1.19
Chemicals	Production of carbon black	-	-	2	0.52	-	-	-	-	-	-	-	-	-	-
	Production of nitric acid	-	-	-	-	1	0.11	-	-	-	-	-	-	1	0.16
	Production of adipic acid	-	-	-	-	-	-	1	0.08	-	-	-	-	-	-
	Production of glyoxal and glyoxylic acid	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production of ammonia	-	-	1	0.35	2	1.05	2	1.74	-	-	-	-	-	-
	Production of bulk chemicals	1	0.36	13	3.29	7	1.05	3	1.07	-	-	1	0.17	2	0.21
	Production of hydrogen and synthesis gas	1	0.08	2	0.30	2	0.33	1	0.24	-	-	1	1.14	1	0.06
	Production of soda ash and sodium bicarbonate	-	-	1	0.14	-	-	2	0.31	-	-	-	-	-	-
Sum of all stationary installations		21	5.98	90	39.79	31	8.27	52	17.29	9	6.25	11	4.89	60	19.72

3.1.4 Emitter locations in relation to infrastructure units

In addition to the potential subsurface storage sites discussed in the previous section based on the depictions seen in Figure 9 (DSA storage) and Figure 10 (salt formation storage), other aspects and locational features, such as basic infrastructures, will play a crucial role in the selection process of suitable national and regional emitter clusters for a potential CEEGS deployment. Therefore, the identified emitter clusters are put into relation to other infrastructure elements relevant for a potential CEEGS system such as:

- the existing gas pipeline network (natural gas) and established commercial large-volume storage facilities (caverns, aquifers, etc.) as prerequisite for a CO₂ pipeline network,
- the available rail and road network as well as major shipping ports for transportation of goods, machinery and required raw material streams,
- deployed renewable power plants for electricity supply of the core and peripheral CEEGS system components and
- the existing national transmission network for high-voltage (HV) electricity transmission featuring potential infeed nodes/substations.

The German natural gas (NG) pipeline network is shown in Figure 11 for different pipeline diameters and in relation to the emitter clusters 1 to 6, including geospatial information regarding major shipping ports and established subsurface NG storages (caverns and aquifers). The NG pipeline network or sections of it could be repurposed for the transport of CO₂ between the location of the CEEGS facility and the respective single emitter/emitter cluster locations, depending on the technical and economic feasibility and the availability of suitable subsurface storage units for CO₂.

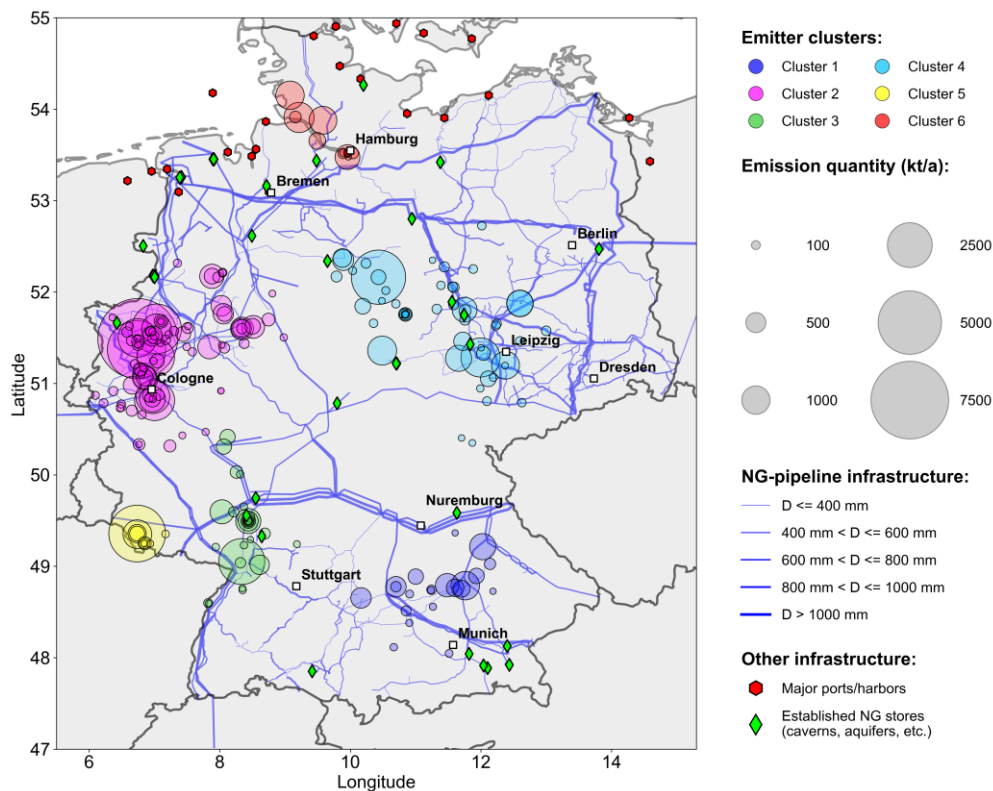


Figure 11: NG pipeline network alongside established commercial subsurface storages in Germany.

It becomes evident, that all emitter clusters are characterized by at least some access to the large-capacity NG network. Some emitter clusters (e.g. clusters 4, 5 and 6) also include larger single emitting installations without a direct access to the NG network in their vicinity. Furthermore, clusters 1, 2, 3,

and 6 also have numerous and already established large-volume storage sites with a reasonable distance to their single emitter locations. All relevant NG storage sites reported by Gas Storage Europe are summarized in Table 11 (GSE, 2024).

Table 11: Established commercial NG storages in Germany based on the GSE database (GSE, 2024).

NG storage type	Number of stores	Storage capacity (TWh)
Salt caverns	44	159.8
Depleted fields	11	94.3
Aquifers	6	4.4
Total	61	258.5

Figure 12 depicts the existing rail, road and port (overseas shipping) infrastructure for Germany. All emitter clusters exhibit a very good access to the German rail and road infrastructure. However, clusters 2 and 6 stand out in this regard due to the presence of high capacity inland waterways and ports (river Rhine) and major overseas ports (port of Hamburg), respectively. Cluster 5 lacks relevant high-capacity internal waterways and ports and can therefore be considered more isolated in comparison to the other clusters.

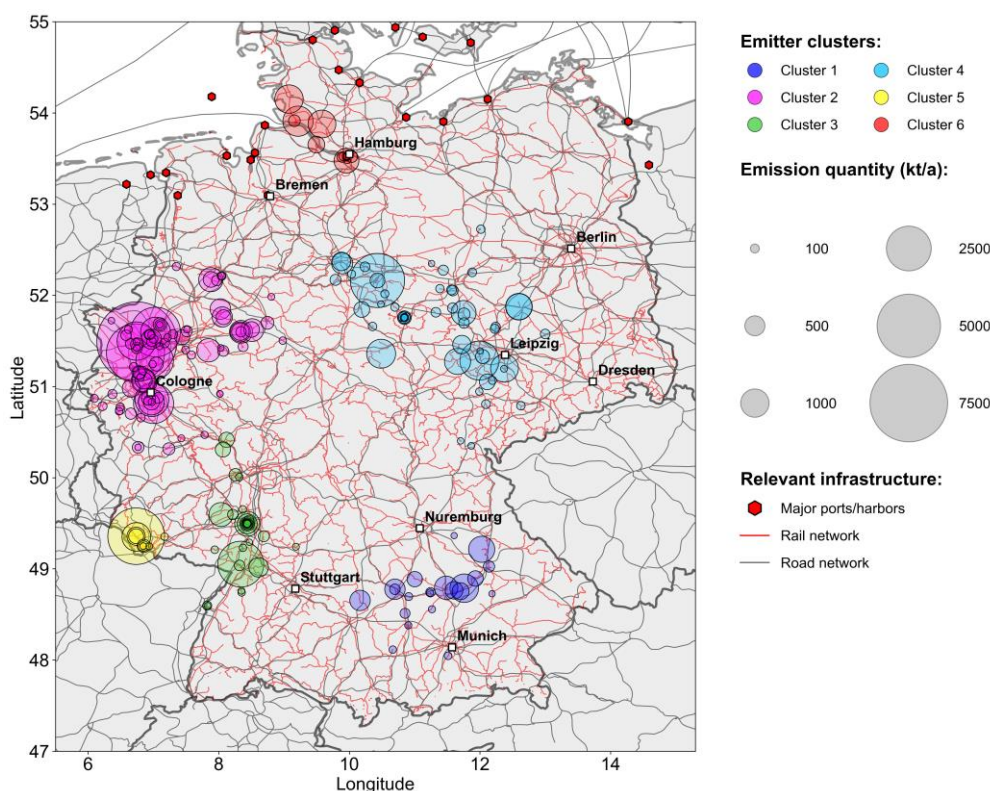


Figure 12: Rail and road network including major overseas shipping ports in Germany.

Figure 13 shows the emitter clusters in relation to the locations of all relevant renewable power plants in Germany. At the time of writing of this report, 735 solar, 112 hydro, 25 wind and 53 biomass power plants are in operation in Germany as retrieved from the Global Power Plant Database (WRI, 2021). A clear concentration of renewable power plants in East Germany and Bavaria can be observed, whereas other regions lack renewable generation capacities (e.g. lower Saxony). From an energy-supply point of view, emitter clusters 1 and 4 exhibit a substantial locational advantage over the other emitter clusters, especially regarding potential large-scale CEEGS systems. Clusters 3 and 5 also feature adequate renewable generation capacities in their vicinity, specifically with regards to their lower overall CO₂ emission quantity to be handled (8.3 Mt and 6.3 Mt, respectively). Emitter cluster 2 will most likely be excluded from further analyses due to the lack of installed renewable capacity close by.

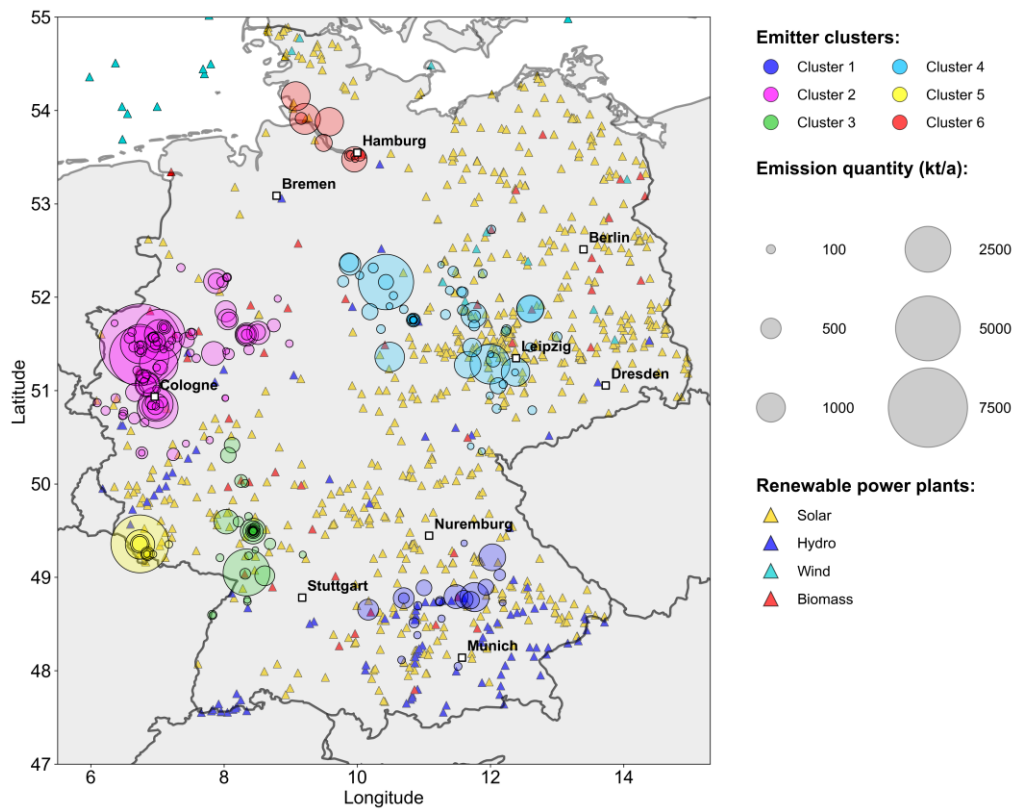


Figure 13: Locations of renewable power plants (solar, hydro, wind and biomass) in Germany.

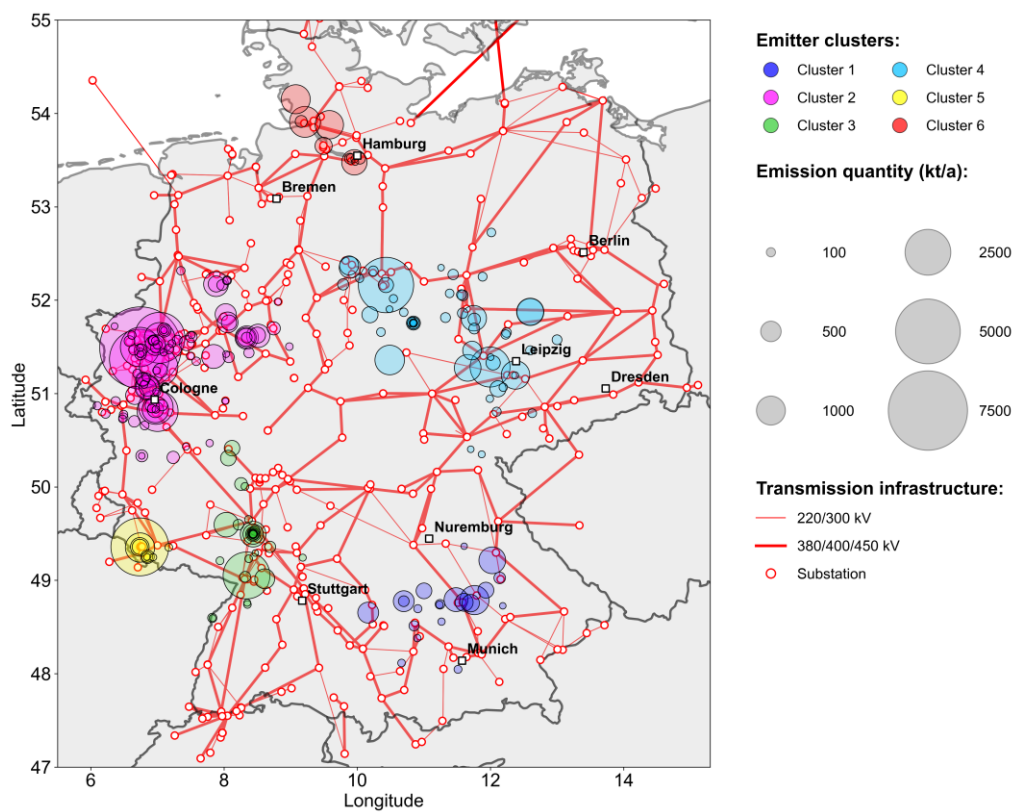


Figure 14: High-voltage (HV) transmission network (approximated paths) for voltages from 220 to 450 kV and respective locations of substations in Germany.

Potential grid-infeed nodes and the availability of the respective HV transmission network is of paramount importance to future renewable energy systems including large-scale energy storage technologies, such as CEEGS. Therefore, Figure 14 displays a basic approximation of the German HV transmission network alongside the locations of potential grid-infeed nodes or substations (transmission voltages ranging from 220 kV to 450 kV grouped into two transmission capacity groups). Almost all identified emitter clusters, as presumed potential areas of CEEGS deployment, feature a well-established access to the national HV transmission grid. Only a few single emitters within the clusters show some sort of isolation from HV lines or substations. However, the current HV network situation most likely will improve due to large-scale grid extension projects by the likes of SuedLink.

A summary of the infrastructural assessment is compiled in Table 12.

Table 12: Quality of infrastructure availability with respect to the identified emitter clusters.

Cluster	NG network and NG stores	Rail, road and shipping ports	Renewable power plants	HV transmission network
1	++	+	++	+
2	++	++	o	++
3	++	+	+	++
4	+	+	++	+
5	-	o	o	++
6	o	++	+	+

3.1.5 National greenhouse gas balance

The CO₂ emissions from hard-to-abate industries, which potentially can be employed as feed stream to future CEEGS systems, are put into relation to the national greenhouse gas balance of Germany of the year 2022, as reported by the European Environmental Agency (EEA, 2024 a). The shown GHG balance excludes emissions or emission reductions from biomass, waste treatment, international bunkers (aviation and navigation), CO₂ capturing as well as land-use, land-use change and forestry.

The total German CO₂ emissions of 2022 (stationary and non-stationary emitters; see Figure 15) amount to 671.47 Mt, of which 627.98 Mt are attributed to energy provision, 40.95 Mt to industrial processes and product use and 2.54 Mt to agriculture. Only 114.78 Mt of the energy-related CO₂ emissions are caused by fuel combustion (provision of heat and/or electricity) for the manufacturing and construction sector. This means, that industrial CO₂ emissions from the manufacturing and construction sector amounts to 155.73 Mt for all involved stationary and non-stationary emitters (23.2 % of the total CO₂ emissions). Further details on the emission composition for industrial processes and product use can be found in Figure 15 c). As indicated in Section 3.1.1, 110.02 Mt of CO₂ emissions of the manufacturing and construction sector originate from 732 stationary installations of hard-to-abate industries (without the 50 kt/year threshold) based on the EUTL emission repository.

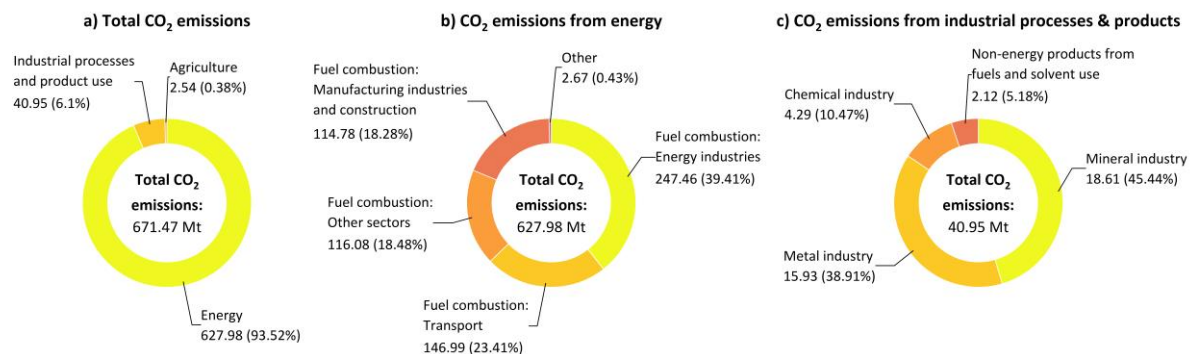


Figure 15: Composition of a) the national total greenhouse gas (GHG) balance, b) the specific GHG emissions of the energy sector and c) the specific GHG emissions from industrial processes and products use for Germany in 2022.

The detailed composition of the CO₂ emissions from fuel combustion in the manufacturing and construction sector (114.78 Mt according to Figure 15 b)) alongside sector-specific emission quantity assessments can be found in Figure 16. Unfortunately, the position “Other” within Figure 16 a) does not include any further specification of the industrial activity, impeding a further detailed and complementary analysis of the reported GHG balance as alternative to the EUTL data and its classification introduced in Section 3.1.1 and Table 8.

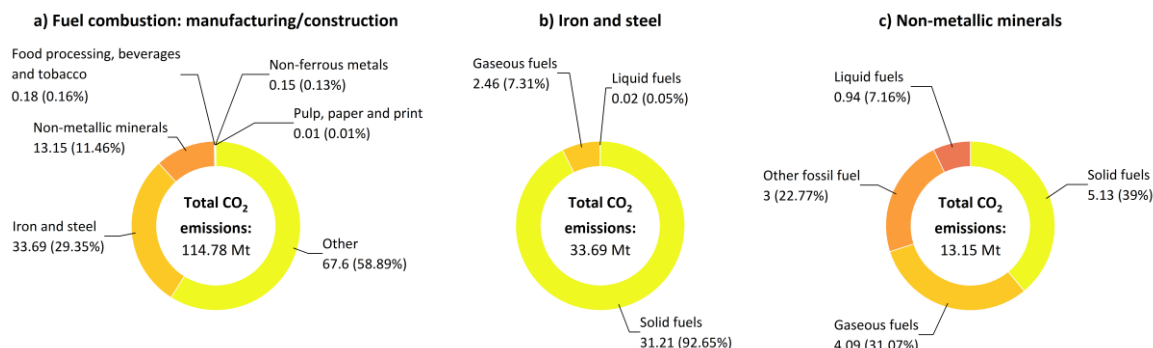


Figure 16: Detailed composition of a) the overall GHG emissions from fuel combustion in manufacturing and construction industries (according Figure 15 b)), b) the specific GHG emissions of iron and steel producers and c) the specific GHG emissions of non-metallic minerals producers for Germany in 2022.

A detailed CO₂ emission assessment of industrial processes and product use (40.95 Mt according to Figure 15 c)) according to all relevant sub-industries (mineral, metal and chemical as well as non-energy products from fuels and solvent use) is depicted in Figure 17.

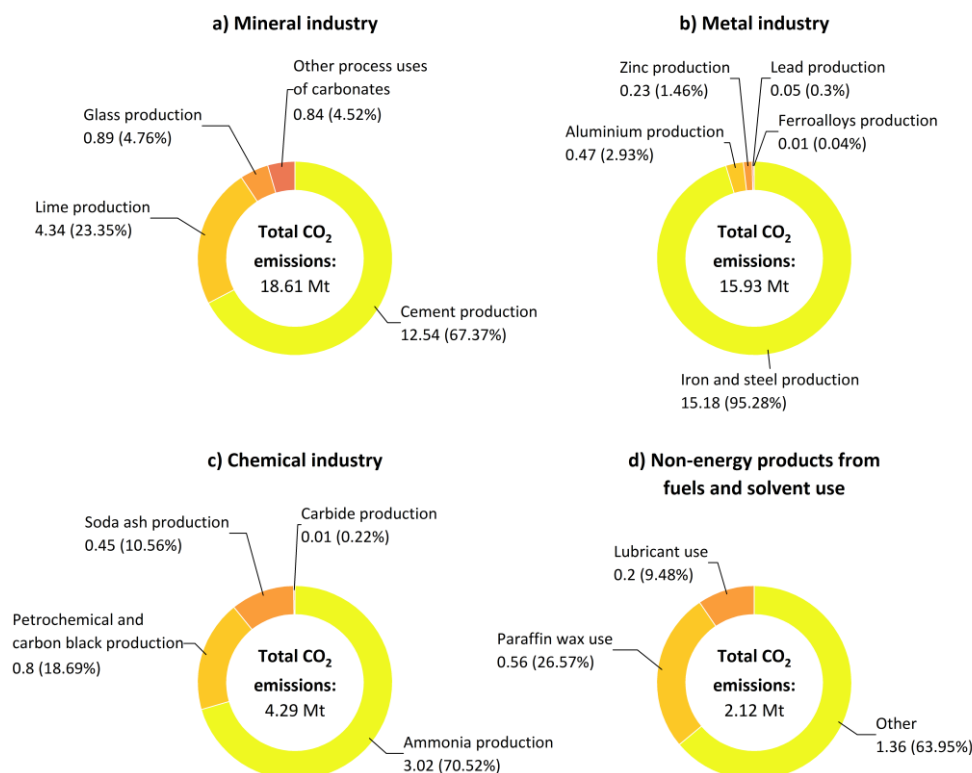


Figure 17: Detailed composition of the overall GHG emissions from industrial processes and products use (according Figure 15 c)) for a) the mineral industry, b) the metal industry, c) the chemical industry and d) non-energy products from fuels and solvent use for Germany in 2022.

To check relevant industrial CO₂ uses (per emitter type and industrial affiliation) with respect to their potential for the stabilization of the national GHG balances, the emitter clusters (obtained from the EUTL data) and the GHG balance subset (emission from manufacturing and construction sector) for Germany for the year 2022 (obtained from the European Environmental Agency) are analysed in view of potential negative emissions. Table 13 contains a detailed summary and comparison of the aforementioned datasets.

Table 13: Summary and comparison of emission data from the national GHG balance, the EUTL repository and the outcome of the regional emitter clustering for Germany in 2022.

CO ₂ emission class	Emission quantity (Mt)	Number of installations (-)	Share of total GHG balance	Share of total GHG subset
GHG balance total ^{a,b}	671.47	-	100 %	-
GHG balance subset ^{a,b} (manufacturing and construction sector)	155.73	-	23.2 %	100 %
Stationary EUTL emitters GER ^c (with threshold of 50 kt/year)	102.18	274	15.2 %	65.6 %
Emitter cluster 1	5.98	21	0.9 %	3.8 %
Emitter cluster 2	39.79	90	5.9 %	25.6 %
Emitter cluster 3	8.27	31	1.2 %	5.3 %
Emitter cluster 4	17.29	52	2.6 %	11.1 %
Emitter cluster 5	6.25	9	0.9 %	4.0 %
Emitter cluster 6	4.89	11	0.7 %	3.1 %
Outliers	19.72	60	2.9 %	12.7 %

^a including stationary and non-stationary emitters;

^b different reporting classes for the emitter categories;

^c also contain emission from on-site energy production.

It is evident, that all relevant CO₂ emissions from the manufacturing and construction sector (155.73 Mt from stationary and non-stationary emitters) reflect a substantial share of the overall national GHG balance (23.2 %). Focussing on stationary emitters, which have been largely employed and analysed in this study, a maximum reduction potential of 102.18 Mt (15.2 % of the total GHG balance) is identified. However, it is clear that not the complete CO₂ emissions from the studied hard-to-abate industries will be utilisable due to technical, economic and infrastructural/transport constraints and limitations.

Given the outcome of the emitter clustering, the GHG stabilization potential is very limited today with usable CO₂ emissions ranging between 4.89 Mt (0.7 % of total GHG balance; cluster 6) and 39.79 Mt (5.9 % of total GHG balance; cluster 2). Provided that CO₂ emissions from the energy sector (Figure 15 a) and b)) drastically decrease in the next two decades, the identified emission clusters from hard-to-abate industries could play a major role in achieving negative on the national and European level. However, further detailed regional case studies with a direct and rigorous integration of the CEEGS energy and CO₂ storage concept are required, including:

- Detailed assessment of the actual feasible CO₂ capture quantities and the respective energy demand (detailed emission composition per industry, detailed carbon capture technology review and separation technology selection and transport network analyses),
- Site selection for the underground storage operation,
- Detailed CEEGS deployment study within one or more of the identified industrial emission clusters (determination of the CEEGS capacity and CO₂ quantity requirements, TEA, LCA, etc.) and
- Implementation within the national energy supply framework (already established link to Task 4.4).

3.2 Spain region

3.2.1 Emitters

The EUTL database of Spain contains 1245 emitters of all types of activities, including stationary and non-stationary emitters, for the time series from 2008 to 2023, of which there are reported CO₂ emissions for 647 for the year 2022, with a total amount of 103.21 Mt. For stationary emitters, 618 installations accounts for 96.33 Mt, of which almost 50 % of the emissions comes from combustion of fuels. Selection of activities not related with energy production from combustion, results in 310 industries, ranging from a maximum of 4.8 Mt to 556 t.

Considering only emissions larger than 50kt/year, results in 132 industrial installations with total annual CO₂ emissions of 44.58 Mt. All reporting emitters for Spain abiding to the chosen emission threshold are compiled in Table 14, alongside their respective industrial activity, number of entities, verified CO₂ emissions and emission share. Based on the aforementioned emission statistics and the chosen emission threshold (50 kt/year) it becomes evident, that large-scale emitters dominate the overall CO₂ emissions of hard-to-abate industries in Spain despite the fewer number of installations (132 entities).

Table 14: Data of hard-to-abate CO₂ emissions in Spain for year 2022 summarized by industrial activity for selected emitters greater than 50 kt/year.

Main activity	Activity code (NACE/EUTL)	Number of entities (-)	Verified emissions (Mt)	Emitted CO ₂ (%)
Refining of mineral oil	21	9	13.55	30.40
Production of coke	22	0	0.00	0.00
Metal ore roasting or sintering	23	1	0.16	0.36
Production of pig iron or steel	24	11	5.75	12.89
Production or processing of ferrous metals	25	2	0.11	0.24
Production of primary aluminium	26	1	0.57	1.27
Production of secondary aluminium	27	0	0.00	0.00
Production or processing of non-ferrous metals	28	3	0.25	0.56
Production of cement clinker ^a	29	26	11.63	26.10
Production of lime, or calcination of dolomite/magnesite ^a	30	13	2.18	4.89
Manufacture of glass ^b	31	17	1.48	3.33
Manufacture of ceramics ^c	32	16	1.49	3.35
Manufacture of mineral wool	33	1	0.05	0.12
Production or processing of gypsum or plasterboard	34	0	0.00	0.00
Production of pulp ^d	35	4	0.43	0.97
Production of paper or cardboard ^d	36	10	1.25	2.81
Production of carbon black	37	1	0.13	0.29
Production of nitric acid	38	1	0.39	0.87
Production of adipic acid	39	0	0.00	0.00
Production of glyoxal and glyoxylic acid	40	0	0.00	0.00
Production of ammonia	41	1	0.42	0.94
Production of bulk chemicals	42	11	2.83	6.35
Production of hydrogen and synthesis gas	43	3	0.85	1.90
Production of soda ash and sodium bicarbonate	44	1	1.06	2.38
Sum of all stationary installations		132	44.58	100

^a some entities still used old ETS activity codes (e.g. "6 - Installations for the production of cement clinker in rotary kilns or lime in rotary kilns or in other furnaces") and therefore the linked reported and verified emissions might be incorrect;

^b including production of glass fibre;

^c includes all installations for the "manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain";

^d some entities still used old ETS activity codes (e.g. "9 - Industrial plants for the production of (a) pulp from timber or other fibrous materials (b) paper and board") and therefore the linked reported and verified emissions might be incorrect.

Most of the emissions are related to the refining of mineral oil and production of cement, accounting for 56.50 % of the hard-to-abate emissions, reaching 25.18 Mt for 35 emitters. Next, the production of pig iron or steel with 5.75 Mt, which represents 12.89 %, and production of bulk chemicals with 2.83

Mt (6.35 %), both with 11 emitters. The rest of the industrial activities make up approx. a quarter of the selected emissions, which individually represent less than 5 % of the total hard-to-abate emissions (75 installations). The geographical distribution of the emitters according to their main industrial sector and annual emission quantity is shown in Figure 18.

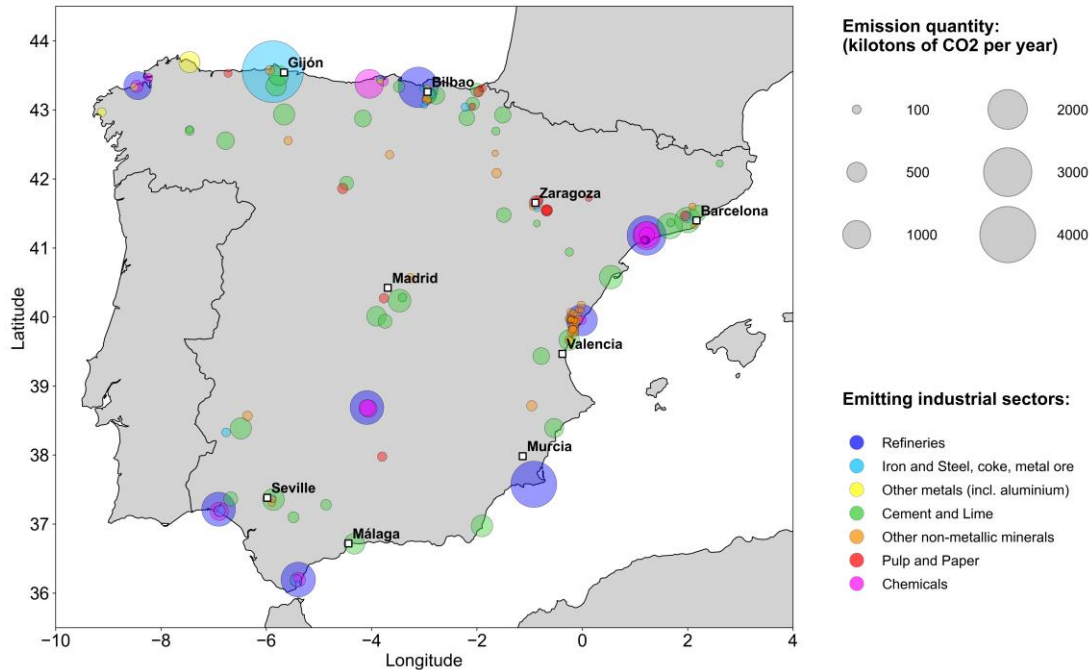


Figure 18: Location and emission quantity (in kilotons) of hard-to-abate emitters grouped by industrial sectors for Spain and the year 2022.

The largest single emitter is the steel plant of Avilés, near Gijón. Refineries and chemical industries are mainly located in the ports, where oil and gas are received from ships and pipelines, so they have a peripheral distribution. These are La Coruña, San Sebastián and Bilbao, on the north coast; Tarragona, Castellón and Cartagena, on the east coast; and Algeciras and Huelva in the South. A particular case is that of Puertollano, in the south-central area of the peninsular interior, where the industry is linked to former exploitation of coal and shale oil. The cement and non-metallic industries are more dispersed, but conditioned by areas of production and consumption.

3.2.2 Storage sites

Figure 19 a) shows 95 suitable geological structures for CO₂ storage from previous works. This database includes 4 saline aquifers in depleted hydrocarbon fields, one of them offshore. Next step will be a selection of the most suitable traps according to the mandatory criteria of D2.4. Figure 19 b) shows the map with 151 evaporite structures proposed as the most suitable for developing storage in salt cavities. Unlike DSA, this layer may include structures above the depth for keeping CO₂ in supercritical state. Additional selection will be made according to the criteria in D2.4 for salt cavities. Both DSA and evaporite formations are located in the sedimentary basins, which occupy the central and eastern part of the Iberian Peninsula (see Figure 5 in Section 2.2.2). Therefore, no suitable sites can be found in the western part, dominated by an ancient Palaeozoic basement.

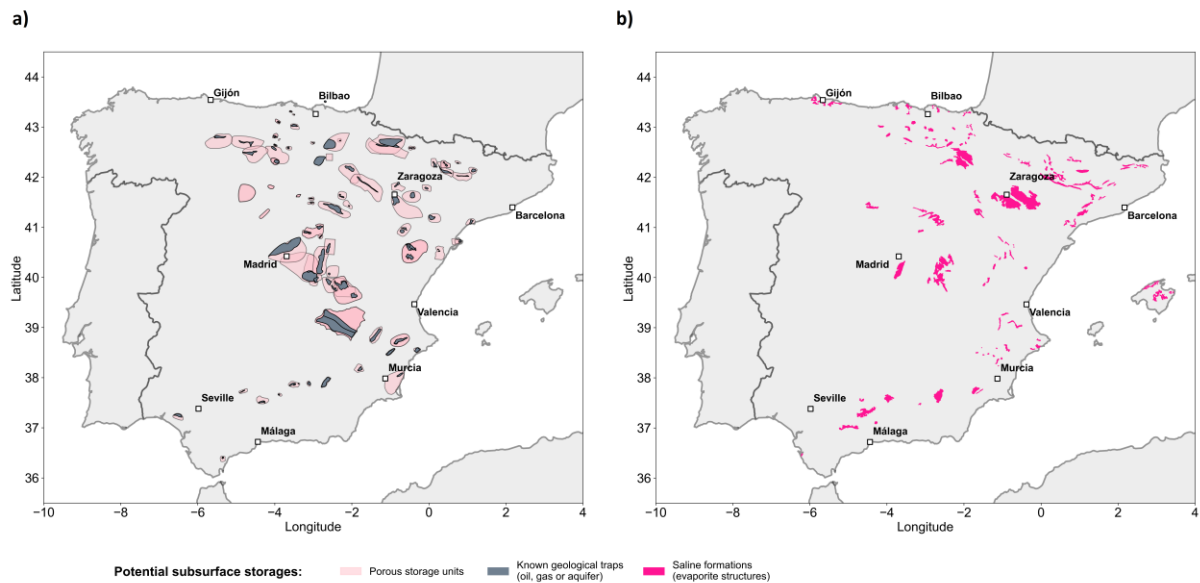


Figure 19: Potential CO₂ storage areas in Spain for a) DSA and known geological traps (depleted oil/gas fields or aquifers) and b) saline formations (evaporite structures).

3.2.3 Clustering and scenarios

Clustering of the emitters, using the DBSCAN algorithm, reveals 7 groups., located in the main industrial areas near the ports in Gijón (Asturias), Bilbao (Basque Country), Tarragona-Barcelona (Catalonia), Valencia-Castellon and Huelva (Andalusia). Also, clusters in the inner main cities of Madrid and Zaragoza can be seen (Figure 20).

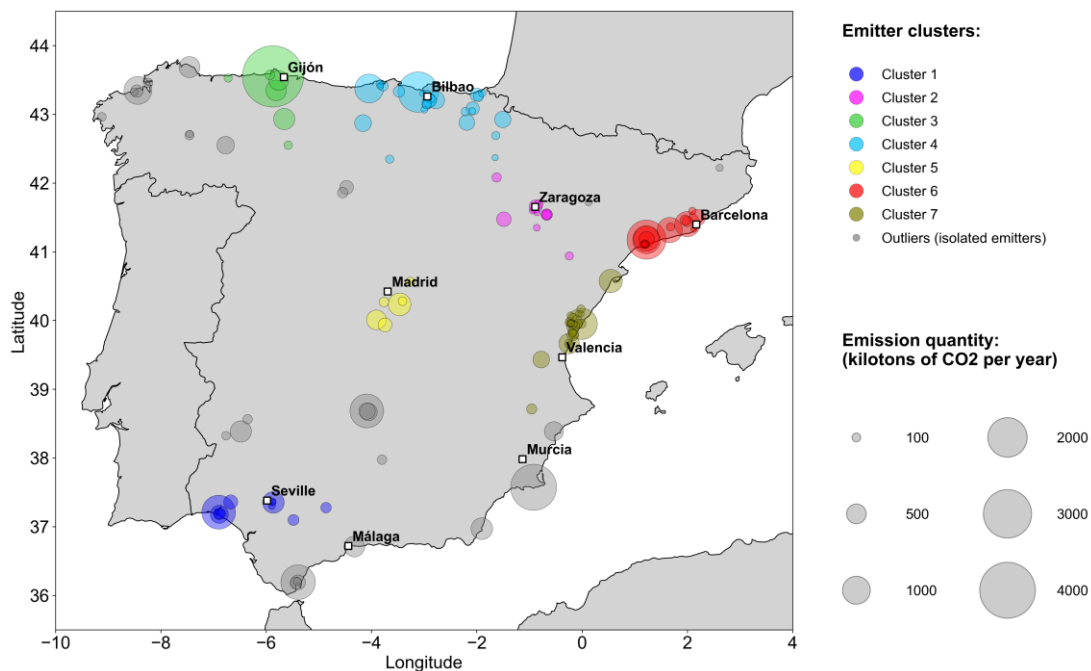


Figure 20: Location and emission quantity (in kilotons) of the identified emitter clusters (based on the DBSCAN algorithm) for Spain and the year 2022.

The largest emission clusters appear to be clusters 6 (6.92Mt), 4 (6.76Mt) and 3 (6.72Mt). Cluster 3 has only 7 facilities but its high volume of emissions is due to the large steel plant that represents more than 70% of the emitted CO₂ of the cluster. However, clusters 4 and 6 are made up of 26 and 17 facilities respectively. Clusters 5 and 6 have less relevance as to the amount emitted. Cluster 7 has an

intermediate value (see Table 15). Outliers represent a significant amount of hard-to-abate emissions, especially from some refineries and cement plants.

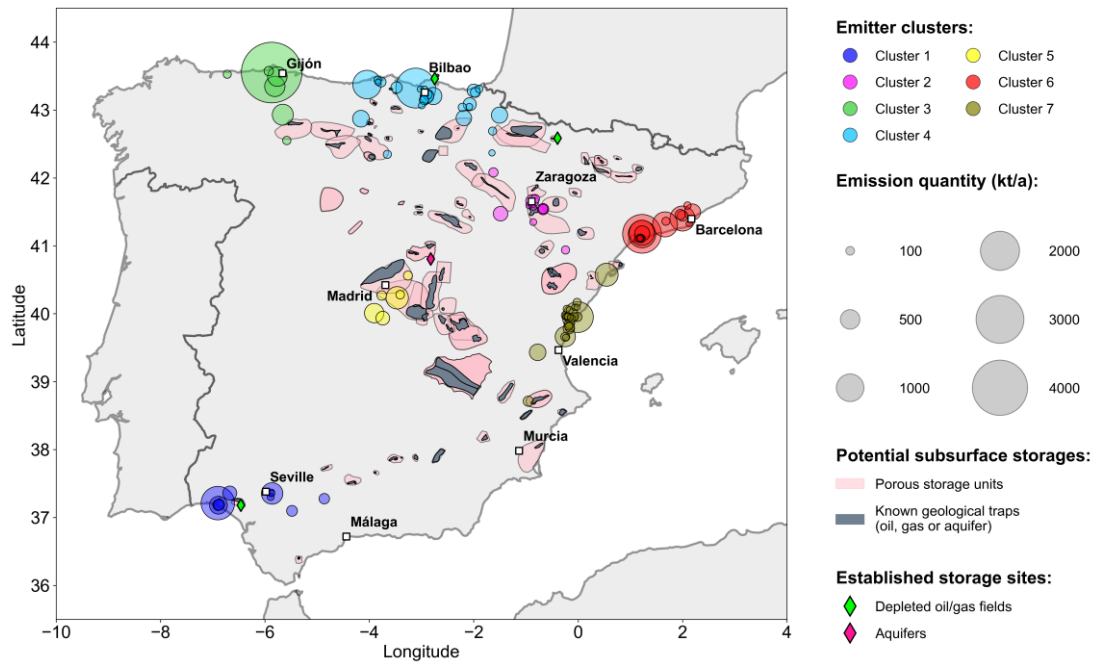


Figure 21: Location and emission quantity (in kilotons) of the identified emitter clusters in relation to potential DSA CO₂ storage sites for Spain.

Overlapping the clusters with the storage sites, shows that while most of the industrial clusters are in coastal areas, storage sites are mostly located in the interior of the country. Promising areas for defining scenarios are located around the cities of Madrid and Zaragoza, where both DSA and salt formations coincide with clusters 5 and 2, respectively (Figure 21). Other possible places are DSA overlapping clusters 4, 3 and possibly cluster 1. Clusters 6 and 7 have storage sites in their vicinity, although they are somewhat far away, but given the number of facilities and the amount of CO₂ emitted, it would be advisable to do a thorough analysis of the transportation possibilities. Cluster 2 will surely be discarded.

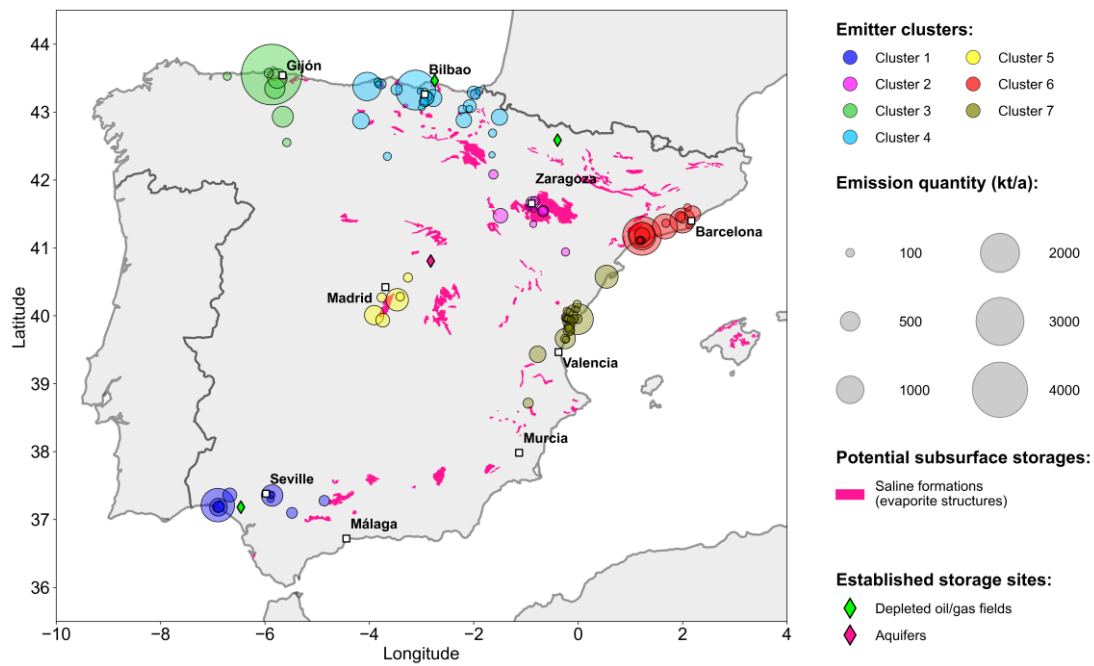


Figure 22: Location and emission quantity (in kilotons) of the identified emitter clusters in relation to potential CO₂ storage sites in salt formations for Spain.

Table 15: Detailed emission data (only emitters with quantities 50 > kt CO₂ per year) of the retrieved emission clusters in Spain for 2022.

Sector	Main activity	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5		Cluster 6		Cluster 7		Outliers	
		No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)	No. of em.	CO ₂ (Mt)
Refineries	Refining of mineral oil	1	1.47	-	-	-	-	1	2.08	-	-	2	2.05	1	1.24	4	6.71
Iron and Steel, coke, metal ore	Production of coke	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Metal ore roasting or sintering	1	0.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production of pig iron or steel	1	0.07	1	0.05	1	4.81	5	0.39	-	-	1	0.15	-	-	2	0.28
Other metals (incl. aluminium)	Production or processing of ferrous metals	-	-	-	-	-	-	1	0.05	-	-	-	-	1	0.06	-	-
	Production of primary aluminium	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0.57
	Production of secondary aluminium	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production or processing of non-ferrous metals	-	-	-	-	-	-	1	0.07	-	-	-	-	-	-	2	0.18
Cement and Lime	Production of cement clinker	2	0.86	1	0.28	2	1.08	5	1.54	3	1.40	3	1.98	3	1.59	7	2.91
	Production of lime, or calcination of dolomite/magnesite	2	0.30	2	0.15	1	0.54	4	0.82	1	0.10	1	0.09	-	-	2	0.18
Other non-metallic minerals	Manufacture of glass	2	0.12	2	0.17	2	0.21	3	0.30	1	0.11	2	0.12	4	0.34	1	0.12
	Manufacture of ceramics	-	-	-	-	-	-	-	-	-	-	-	-	16	1.49	-	-
	Manufacture of mineral wool	-	-	-	-	-	-	1	0.05	-	-	-	-	-	-	-	-
	Production or processing of gypsum or plasterboard	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pulp and Paper	Production of pulp	-	-	-	-	1	0.09	2	0.20	-	-	-	-	-	-	1	0.14
	Production of paper or cardboard	-	-	5	0.76	-	-	1	0.06	1	0.12	1	0.14	-	-	2	0.18
Chemicals	Production of carbon black	-	-	-	-	-	-	1	0.13	-	-	-	-	-	-	-	-
	Production of nitric acid	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0.39
	Production of adipic acid	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production of glyoxal and glyoxylic acid	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production of ammonia	1	0.42	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Production of bulk chemicals	1	0.16	-	-	-	-	-	-	-	-	6	2.09	1	0.11	3	0.47
	Production of hydrogen and synthesis gas	-	-	-	-	-	-	-	-	-	-	1	0.30	-	-	2	0.54
	Production of soda ash and sodium bicarbonate	-	-	-	-	-	-	1	1.06	-	-	-	-	-	-	-	-
Sum of all stationary installations		11	3.57	11	1.41	7	6.72	26	6.76	6	1.72	17	6.92	26	4.84	28	12.65

3.2.4 Emitter locations in relation to infrastructure units

There is an evident relationship between gas and oil pipelines and the industrial clusters (Figure 23). Gas pipelines connect ports, where regasification plants inject gas from LNG vessels to the pipeline network. In addition, gas from North Africa through gas pipelines is also injected. This network is arranged with a North-South orientation, so both industrial clusters and ports are connected from one side of the country to the other. Also, one branch runs along the eastern coast and connects with the main network. In this way, all the emitter clusters could reuse NG pipelines for CO₂ transport or use new specially built gas pipelines along oil and gas pipeline corridors.

There are only 3 onshore NG storage sites, with a total capacity, of 3700 Mm³. They are located far from the emitter clusters. However, connection through existing pipelines could allow the use of the Marismas site for cluster 1, Yela site for cluster 6 and Serrablo site for cluster 2.

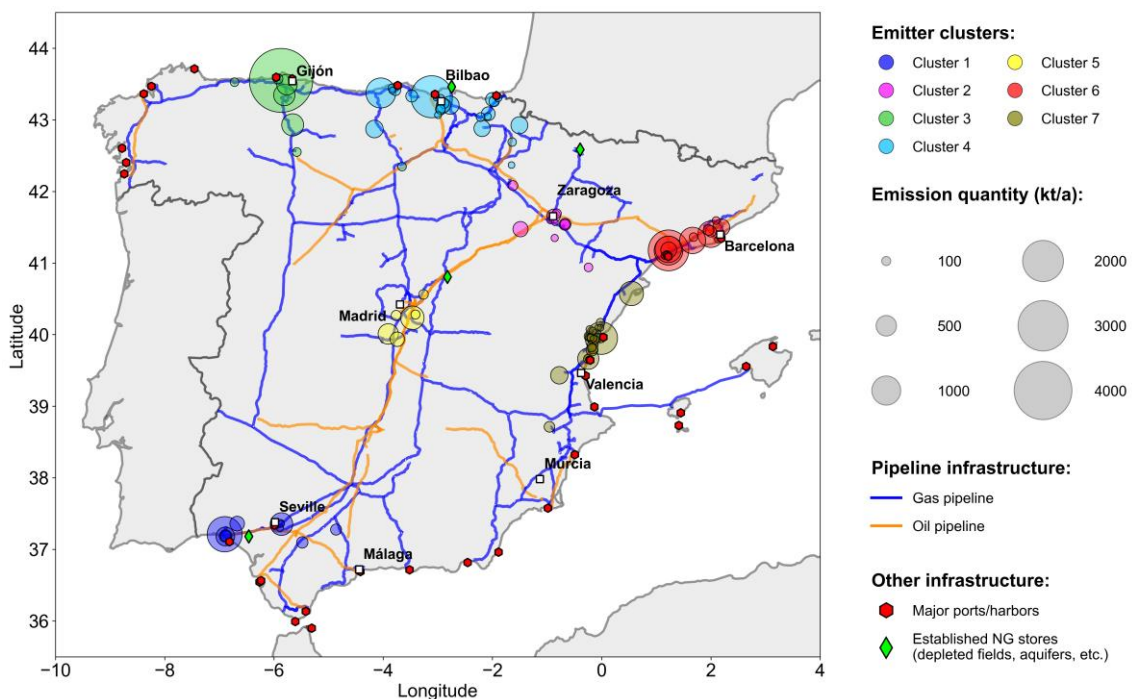


Figure 23: NG and oil pipeline network alongside established commercial NG subsurface storages in Spain.

There is also a good connection between emitter clusters and the rail and road infrastructure and ports (Figure 24). Major cities and industries are located in transportation nodes. The clusters are also near the main ports, except for clusters 2 and 5.

In Spain the main renewable power plants comprises 342 wind, 243 solar, 124 hydro and 1 biomass (WRI, 2022) (see Figure 25), with a total capacity of 31.92 GW. Wind generation is widespread all over the country, although areas with higher capacity are in the northern part in a NW-SE orientation and in the eastern side in a N-S orientation. Hydraulic power is concentrated in mountainous zones, far from industrial areas. Solar generation has the main capacity in the southern half, although here thermal solar generation is especially relevant, which includes 49 operating facilities in the country with a capacity of 2.3 GW (Protermosolar, 2024). Biomass is not relevant. Clusters 2, 3, 4, 6 and 7 would benefit more from wind power generation and cluster 1 from solar, though clusters 3 and 4 could also use a mix with hydro generation. Cluster 5 is in disadvantage for the use of renewables. Further analysis should be done in terms of proximity and energy needs by cluster in order to choose the most adequate renewable power source.

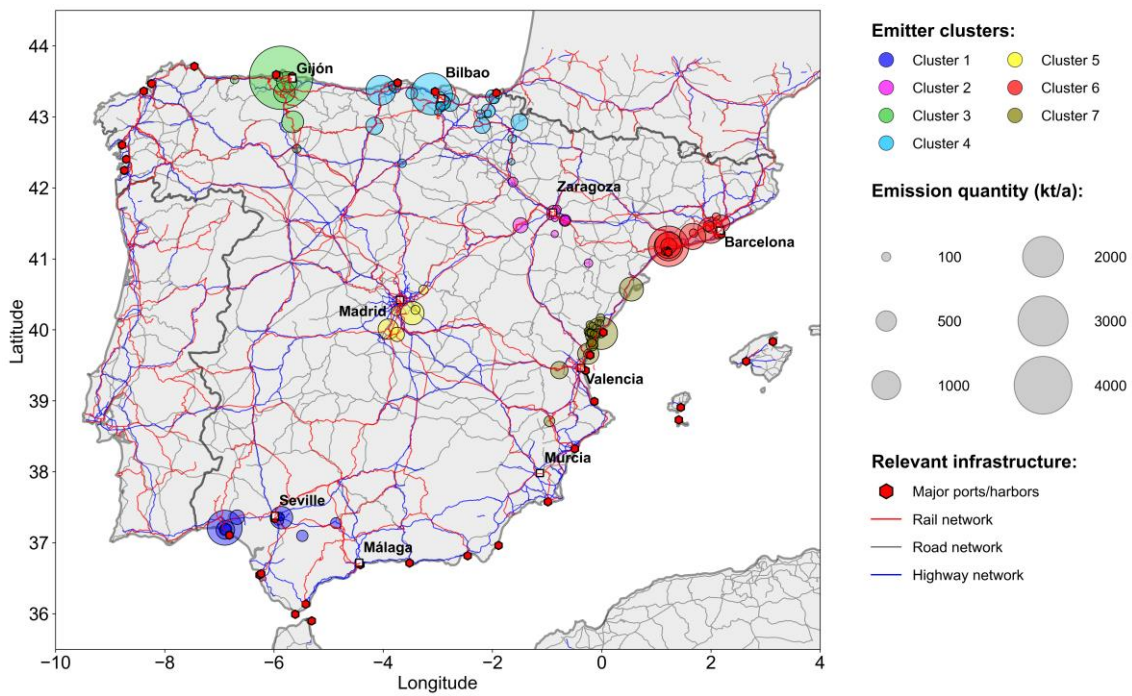


Figure 24: Rail, road and highway network including major overseas shipping ports in Spain.

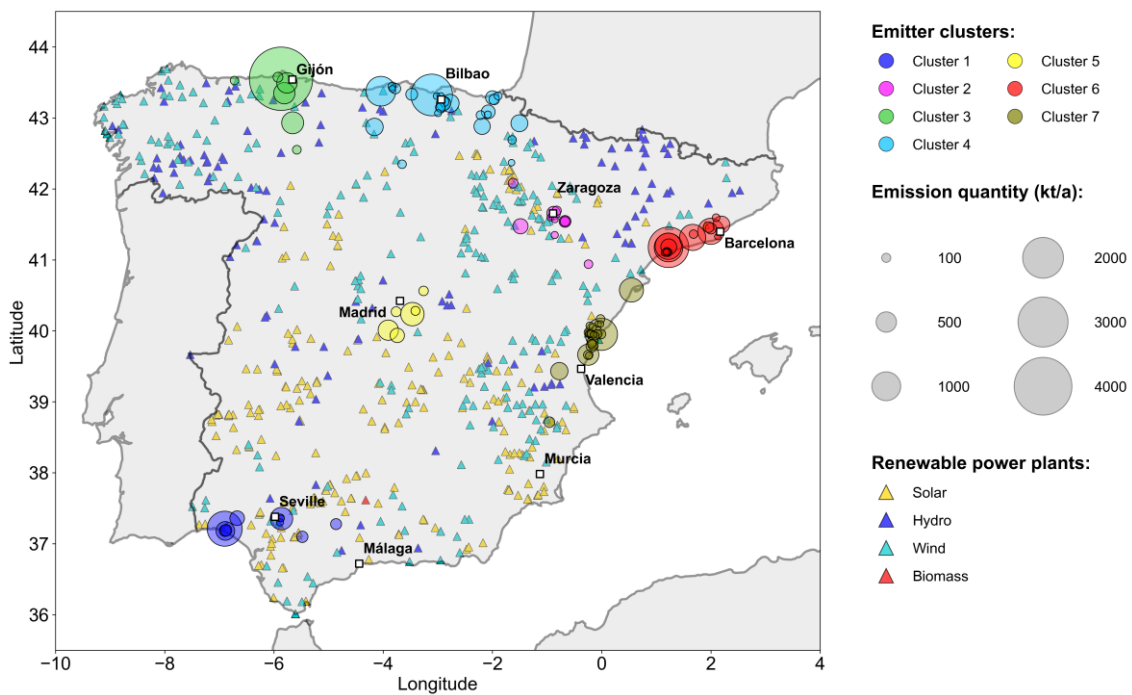


Figure 25: Locations of renewable power plants (solar, hydro, wind and biomass) in Spain.

With respect to the transmission infrastructure, Figure 26 shows that all the clusters are well connected to the HV network.

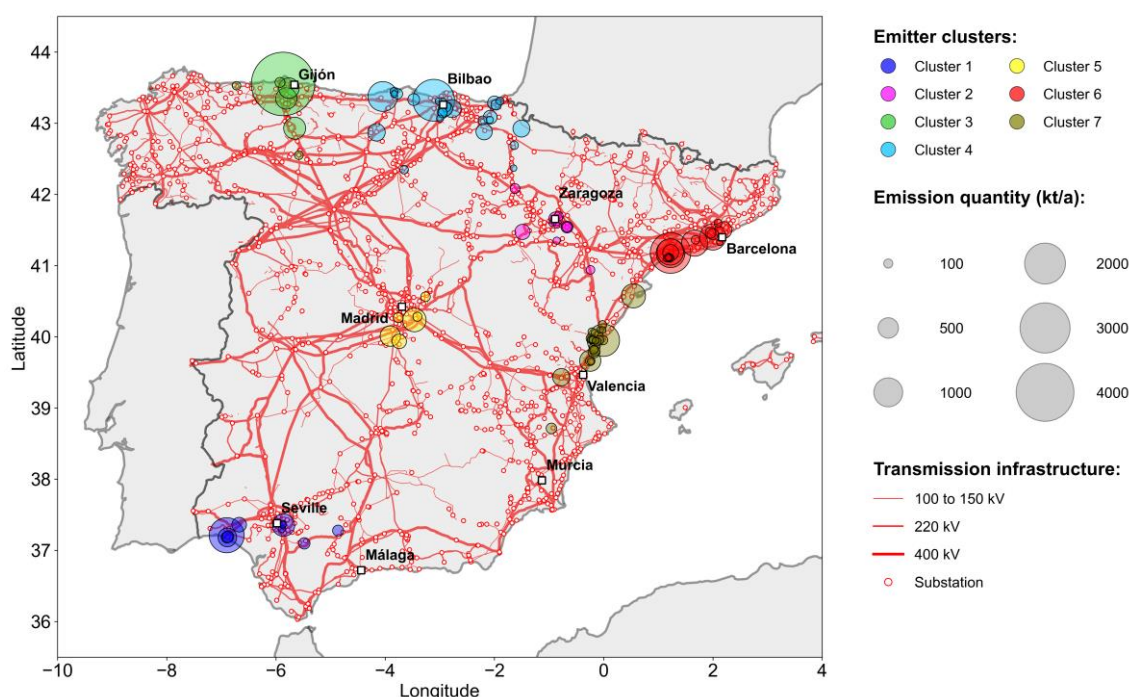


Figure 26: High-voltage (HV) transmission network for voltages from 100 to 400 kV and respective locations of substations in Spain.

3.2.5 National greenhouse gas balance

In this section, a comparison between hard-to-abate emissions and GHG balance from (EEA, 2024 b) is shown, excluding the emissions and emission reductions from biomass, waste treatment, international bunkers (aviation and navigation), CO₂ capturing as well as land-use, land-use change and forestry.

The total Spanish CO₂ stationary and non-stationary emissions for 2022 amount to 234.66 Mt, of which 218.09 Mt are attributed to energy provision, 16.18 Mt to industrial processes and product use and 0.39 Mt to agriculture. Emissions related to fuel combustion for heat and electricity for the manufacturing and construction sector are 36.82 Mt. Hence, industrial CO₂ emissions from the manufacturing and construction sector amounts to 53.0 Mt for all involved stationary and non-stationary emitters (22.6 % of the total CO₂ emissions). Further details on the emission composition for industrial processes and product use can be found in Figure 27 c).

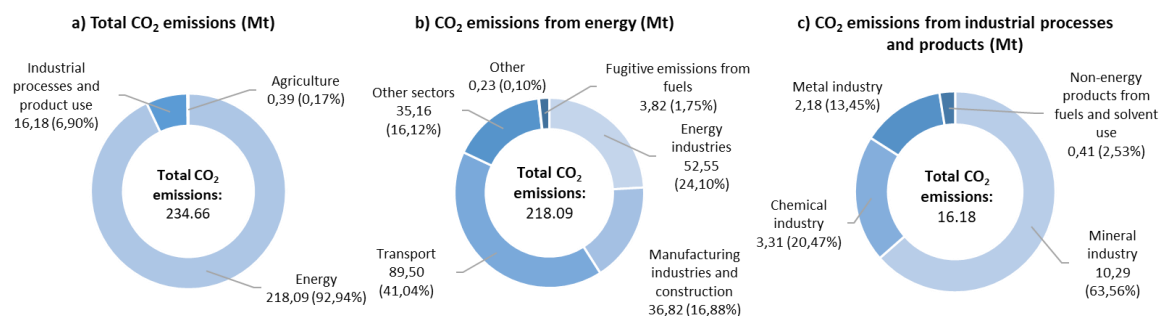


Figure 27: Composition of a) the national total greenhouse gas (GHG) balance, b) the specific GHG emissions of the energy sector and c) the specific GHG emissions from industrial processes and products use for Spain in 2022.

The detailed composition of the CO₂ emissions from fuel combustion in the manufacturing and construction sector (36.82 Mt according to Figure 27 b) alongside sector-specific emission quantity assessments can be found in Figure 28.

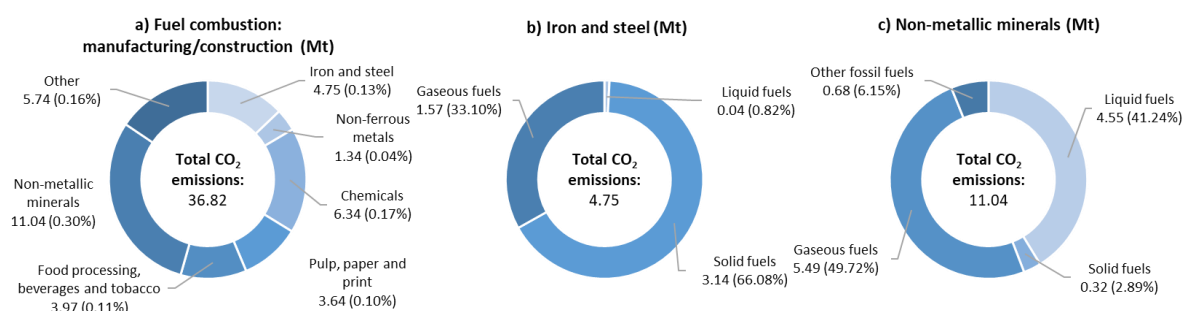


Figure 28: Detailed composition of a) the overall GHG emissions from fuel combustion in manufacturing and construction industries (according Figure 27 b)), b) the specific GHG emissions of iron and steel producers and c) the specific GHG emissions of non-metallic minerals producers for Spain in 2022.

A detailed CO₂ emission assessment of industrial processes and product use (16.18 Mt according to Figure 27 c)) according to all relevant sub-industries (mineral, metal and chemical as well as non-energy products from fuels and solvent use) is depicted in Figure 29.

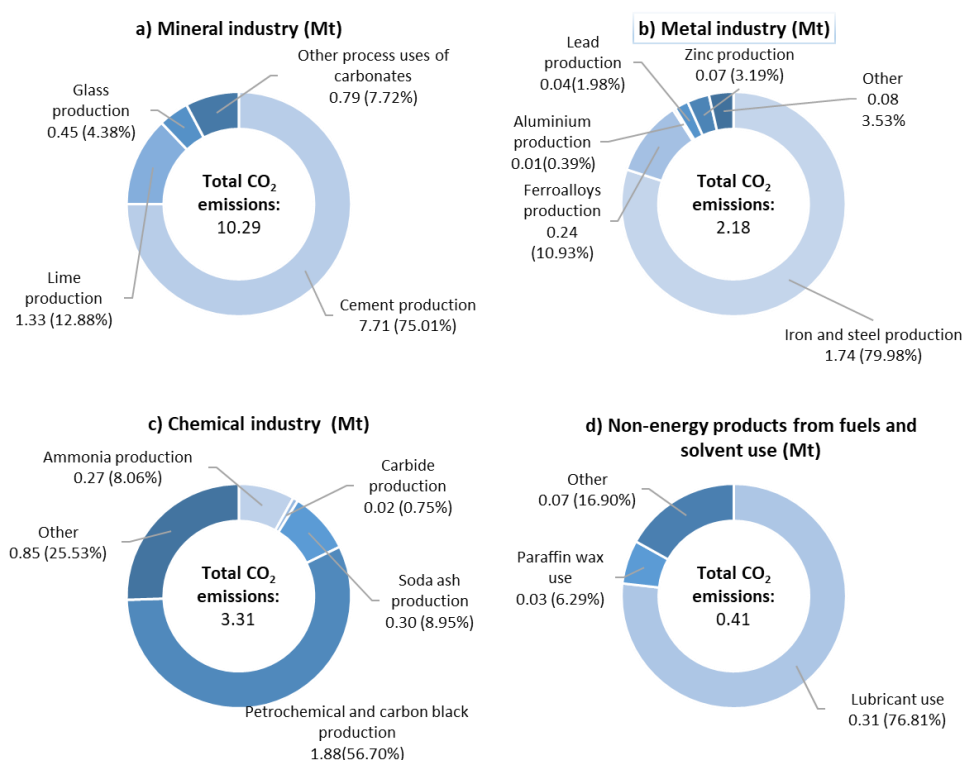


Figure 29: Detailed composition of the overall GHG emissions from industrial processes and products use (according Figure 27 c)) for a) the mineral industry, b) the metal industry, c) the chemical industry and d) non-energy products from fuels and solvent use for Spain in 2022.

Comparison of EUTL emission data and national GHG balance reveals that manufacturing and construction sector represents only 22.59 % of the GHG total balance (Table 16). Selected emitters over 50 kt/year are responsible of the 19 % of the emissions (132 industries), but 84.11 % with respect to the hard-to abate subset. By cluster distribution, clusters 3, 4 and 6 stand out in terms of emissions share both in GHG balance and GHG subset, followed by clusters 7 and 1. Clusters 5 and 2 are less relevant. Considering the number of emission points, cluster 3 represents 12.68 % of the GHG subset emissions with only 7 installations, due to the weight of one of the industries (see Section 3.2.3). Emissions in the other clusters are better distributed.

Table 16: Summary and comparison of emission data from the national GHG balance, the EUTL repository and the outcome of the regional emitter clustering for Spain in 2022.

CO ₂ emission class	Emission quantity (Mt)	Number of installations (-)	Share of total GHG balance	Share of total GHG subset
GHG balance total	234.66	-	100 %	-
GHG balance subset (manufacturing and construction sector)	53.0	-	22.59%	100%
Stationary EUTL emitters (with threshold of 50 kt/year)	44.58	132	19.00%	84.11%
Emitter cluster 1	3.57	11	1.52%	6.74%
Emitter cluster 2	1.41	11	0.60%	2.66%
Emitter cluster 3	6.72	7	2.86%	12.68%
Emitter cluster 4	6.76	26	2.88%	12.75%
Emitter cluster 5	1.72	6	0.73%	3.25%
Emitter cluster 6	6.92	17	2.95%	13.06%
Emitter cluster 7	4.84	26	2.06%	9.13%
Outliers	12.65	28	5.39%	23.87%

4 Conclusions and outlook

In this report, a compilation of data of point CO₂ emitters and suitable formations for CO₂ storage has been done. Also, a common methodology for selection for further scenario definition has been outlined. Verified emissions for year 2022 have been considered. They have been filtered by industrial activity for considering only hard to abate emissions, and a minimum amount of CO₂ emitted has been set in 50kt/year. Emitters have been grouped into clusters by density/proximity and have been overlapped to the proposed formations in order to rank the clusters for later scenario definition.

For Germany, a total of hard-to-abate emissions from the filtered 274 industries sums up 102.18 Mt, with the production of pig iron or steel and refining of mineral oil the being the main emitters, accounting for the 47.09 % of the emissions, and reaching 48.12 Mt for 40 emitters. Next, the production of cement clinker with 18.76Mt, which represents 18.36 %, with 35 emitters, and production of lime, or calcination of dolomite/magnesite with 8.41 Mt (8.23 %), with 46 emitters. Production of bulk chemicals reaches 6.15 Mt with 27 industries. The remaining emissions of the activities sums up approx. 21 Mt, which individually represent less than 5 % of the total CO₂ emissions. The clustering and proximity analysis revealed 6 potential industrial emission clusters.

For Spain, the 132 filtered emitters sum up 44.58 Mt, most of which are related to the refining of mineral oil and production of cement, accounting for the 56.50 % of the hard to abate emissions, reaching 25.18 Mt for 35 emitters. Next, the production of pig iron or steel with 5.75 Mt, which represents 12.89 %, and production of bulk chemicals with 2.83Mt (6.35 %), both with 11 emitters. The rest of the activities sums up a quarter of the selected emissions, which individually represent less than 5 %. The clustering analysis revealed 7 potential industrial clusters for the national case of Spain.

Proposed storage sites are deep saline aquifers and saline formations. For both countries, formation maps and databases with formation attributes have been collected for further selection. For this purpose, selection criteria from deliverable D2.4 will be applied and a ranking of the most suitable ones will be used together with the industrial clusters to define scenarios.

A first analysis revealed some possible scenarios. For the 6 identified clusters for Germany, the most favourable emitter clusters (including an average feasibility judgement for available infrastructures) are clusters 1, 3, 4 and 6 (in conjunction with DSA storage) and clusters 4 and 6 (in conjunction with salt formations). Despite offering the largest emission quantity and ideal infrastructural circumstances, cluster 2 will be discarded a priori due to its relative isolation to suitable storage sites for both DSA and salt formations.

For Spain, clustering reveals the concentration of the main industrial activities on the coastline, around the main ports. However geological storage is mainly inland. Promising areas for defining scenarios are located around the cities of Madrid and Zaragoza, where both DSA and salt formations coincide with clusters 5 and 2, respectively. Other possible places are DSA overlapping clusters 4, 3 and possibly cluster1. Clusters 6 and 7 would need to be studied in depth since they are somewhat far from storage sites. Cluster 2 would surely be discarded.

The purpose of this report is to draw some preliminary conclusions with the data available. As more data comes from other tasks in the project, more refined analysis will be performed and a final version of the document will be submitted at the end of the project. Some recommendations for improvements on the document are given in the next section.

5 Recommendations for document revision

Next, other aspects to consider in future version of this report are mentioned.

- Cluster definition has been proposed in terms of geographical proximity applying selection criteria and algorithms explained in section 2. A revision of the clusters should consider distance in terms of transportation network. For this, layers with main routes, railways and pipelines are be provided.
- Origin of emissions have been selected considering volume of emissions, hard-to-abate ones and geographic situation of the industries. However, some other factors like composition of the gases may constrain the viability of the CEEES deployment. Data about other pollutants is available in the national PRTR databases for both countries, and reported by installation. This may be used to assess if the emissions meet the purity requirements needed for an efficient performance of the system. Other source of data could be the analysis of pollutants by type of industry found in literature. Also, pollutants coming from the underground should be considered. At the moment of writing this report, only short-term simulations have been carried out in the project and no dissolution of minerals have been reported. Long term simulations are programmed in the scope of the Task 3.2 and the results will give valuable information of mobilised compounds to be considered, if any.
- Refinement of the scenarios to be proposed should include energy needs of the industries to balance the energy demand for the full life cycle. Data could come from PRTR databases, literature and from WP3. Electric energy provided by CEEES could be consumed in-situ or distributed through the regional power network. Other energy needs could be included such as heat and cool for industrial processes that CEEES can provide. However, distance limitations for supplying this energy influence the design of the scenarios. For these reasons, it has to be decided if more than one type of scenario, with and without heat and cool, is to be examined.
- Potential CO₂ uses, as a way of achieving negative emissions, should also be included in the proposal of scenarios. An analysis of the industries in the clusters will give an idea of how transversal decarbonisation may be improved by introducing CO₂ into some industrial processes.
- Although some maps with potential storage sites are presented in this report, selection of those which meet the criteria proposed in D2.4 has not been done yet. Storage sites included in this report could be reviewed as new data is published. There is an increasing interest and need for acquiring new data for locating CO₂ storage sites. The EU Commission has a special concern about the accomplishment of the commitments for cutting down emissions. Current and new projects may contribute with new data, which leads to new sites to consider, or already proposed sites to discard.
- The selection of the sites should consider also a rough estimation of the capacity, which ensures a volume for plume setup. Scenario definition must include an estimation of the minimum flow to be provided for the CO₂ plume setup at the estimated injection rate. Once the plume is formed, there will be less demand for CO₂ which could be derived to other uses. Results from D3.2 about injection rates will be included, which will be site specific, depending on the porosity, permeability and heterogeneity of the site.
- As final step scenarios must be combined with the results of the techno economic analysis to be done in Task 6.3. Also, a final review comparing costs for transportation and energy.

6 Nomenclature

Abbreviations

AHP	Analytical hierarchy process
BG	Betic Cordillera and Guadalquivir Basin
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BKG	Bundesamt für Kartographie und Geodäsie
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CCUS	Carbon capture, utilization and storage
CD	Cantabrian Range and Duero Basin
CEEES	CO ₂ -based Electrothermal Energy and Geological Storage
CO ₂	Carbon dioxide
CSIC	Consejo Superior de Investigaciones Científicas
DBSCAN	Density-based spatial clustering of applications with noise
DIW	Deutsches Institut für Wirtschaftsforschung
DSA	Deep saline aquifer
EEA	European Environmental Agency
EGR	Enhanced gas recovery
ENI	Ente Nazionale Idrocarburi
ETC/ACM	European Topic Centre on Air Pollution and Climate Change Mitigation
ETC/CME	European Topic Centre on Climate Change Mitigation and Energy
ETS	Emissions Trading System
EU	European Union
EUTL	European Union Transaction Log
FAIR	Findable, Accessible, Interoperable and Reusable
GHG	Greenhouse gas
GIS	Geographic information system
GM	Google Maps
GSE	Gas Storage Europe
GSEU	Geological Service for Europe
HTML	Hypertext Markup Language
HTTPS	Hypertext Transfer Protocol Secure
HV	High-voltage (transmission lines)
HZDR	Helmholtz-Centre Dresden-Rossendorf e.V.
ID	Identification
IESDB	Iberian Evaporite Structure Database
IGME	Instituto Geológico y Minero de España
IGN	Instituto Geográfico Nacional
IT	Tajo and Almazán Basin
LBEG	Geological Survey of Lower Saxony
LNG	Liquefied natural gas
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NG	Natural gas
NGB	North German Basin
OSM	Open Street Map
PE	Pyrenees and Ebro Basin
PRTR	Pollutant Release and Transfer Register
SMB	South German Molasse Basin
TNO	Toegepast Natuurwetenschappelijk Onderzoek
URG	Upper Rhine Graben
WRI	World Resources Institute

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