Key data for characterising sources, transport options, storage and uses in the promising regions

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Executive summary

STRATEGY CCUS aims to produce detailed planning for CO_2 Capture, transport, utilisation and storage (CCUS) in eight regions of southern and eastern Europe, where previous studies and projects have identified the technology as essential to reduce greenhouse gas emissions and, hence, mitigate climate change.

Each of the promising regions, Ebro Basin (Spain), Galati Region (Romania), Lusitanian Basin (Portugal), Northern Croatia, Paris Basin (France), Rhone Valley (France), Upper Silesia (Poland) and West Macedonia (Greece), is known to possess specific strengths to implement CCUS, but detailed planning of CCUS clustering and network development requires collecting information at the local level on six groups of technical features relevant to describe the potential for developing ICCUS clusters, i.e., i) emissions; ii) area; iii) industry; iv) transport infrastructures and v) storage; vi) ongoing and potential utilisations for CO_2.

Local teams in each of the regions conducted assessments related to each of the technical features and implemented a methodology to produce a preliminary overview of the technical potential to develop ICCUS clusters ad networks.

The eight STRATEGY CCUS promising regions have identified 174 industrial and power facilities with current CO_2 emissions that amount to 121.5 Mt/y. The Ebro Basin, in Spain, seems to present the most complete set of conditions to deploy the technology, with a diversified industrial sector, in which emission sources are concentrated in a few hotspots of facilities, and with a level of industry integration that seems to be aware and motivated to engage in ICCUS. Other regions present also very good conditions for building clusters. It could be argued that the configuration and diversity of the industrial sources in the Rhone Valley is ideal for defining a network of capture and transport of CO_2. There is even the potential for relevant CO_2 utilisation in the chemical sector, for synthetic fuels and for mineral carbonation, again benefitting from the highly diversified industrial fabric.

Ongoing CO_2 utilisation is incipient, but it can become an important factor for some of the regions in STRATEGY CCUS, at least in the early stages of CCUS deployment. CO_2-EOR should provide the first large scale opportunities in Northern Croatia, where CO_2-EOR is already a reality, but also at the Galati Region in Romania. Both the Galati Region or Northern Croatia have a good storage potential in well known depleted hydrocarbons fields, either abandoned or still under production. Scenarios need to take into account the volume of CO_2 avoided, as not only hydrocarbons are produced, (and a fraction of the injected CO_2 will after some time also be produced in the wells).

Other large-scale CO_2 utilisations are foreseen in connection to the green hydrogen, namely in Portugal, where the Strategy for Hydrogen relies in the ability to capture large volumes of CO_2 to induce methanation and other chemical processes to produce synthetic natural gas and other synthetic fuels (such as aviation fuels). That solution will, however, not be enough to meet all the CO_2 capture requirements in the region, especially those coming from the process emissions in the cement industry, and geological storage will also be a necessity.

Other regions are more monolithic in their industrial structure, with coal power plants being almost the sole responsible for the large CO_2 emissions in the West Macedonia, in Greece, and Upper Silesia, in Poland. In Greece, a phase-out of coal power plants has been decided, but a CCS-ready

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power plant is being built. A decision to engage in a CCUS project could become of social relevance to maintain jobs in the coal mining activity in the region.

In Upper Silesia coal mining is also a very important economic activity and implementing ICCUS can be instrumental in decoupling it from the CO_2 emissions in the coal power plants. The technical context is certainly very good, with the emissions volumes, distribution of sources and interaction of industry being favourable for deploying ICCUS clusters in the region. The storage conditions are, nonetheless, far from ideal, with a small storage capacity inventoried so far.

In the Paris basin case a considerable number of Energy-From-Waste power plants can provide an opportunity to implement ICCUS projects with negative emissions. This region can also benefit from very good storage potential in depleted hydrocarbon fields, able to provide safe conditions for storage while requiring less investments for increasing the maturity of the storage sites.

The average estimated storage capacity in the eight promising region totals more than 7.7 Gt, the bulk being deep saline aquifers, which represent 95% of the available capacity. Depleted Hydrocarbon Fields provide an added capacity of 240 Mt, while Hydrocarbon fields currently being exploited and with theoretical possibilities to implement CO_2-EOR have an estimated storage capacity of 144 Mt. Uneconomic Coal Beds have very small capacity.

However, maturity of the resource assessments is low, being almost all at Tier 1 and seldom reaching Tier 2 for deep saline aquifers. Depleted hydrocarbon fields in the Paris Basin, Northern Croatia and Galati Region rank as higher assessment tier than the saline aquifers. Raising the maturity of the storage resource assessments is, perhaps, the biggest challenges for a detailed planning for implementing ICCUS networks in the STRATEGY CCUS regions.

The report includes in Appendix I a set of maps for each region about: i) with the location and main features of the sources; ii) with the main features of the storage sites, and; iii) indicating the main features relevant for defining collection and transport networks.

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Key data for characterising sources, transport options, storage and uses in STRATEGY CCUS promising regions

1 Introduction

STRATEGY CCUS aims to produce detailed planning for CO_2 Capture, transport, utilisation and storage (CCUS) in eight regions of southern and eastern Europe, where previous studies and projects have identified the technology as essential to reduce greenhouse gas emissions and, hence, mitigate climate change.

Each of the promising regions, Ebro Basin (Spain), Galati Region (Romania), Lusitanian Basin (Portugal), Northern Croatia, Paris Basin (France), Rhone Valley (France), Upper Silesia (Poland) and West Macedonia (Greece), is known to possess specific strengths to implement CCUS, either because there are significant concentration of industrial sources of CO_2 emissions[1], or because geological storage capacity has been proved to exist, or significant existing / planned utilisations of CO_2, or a combination of these.

However, development of CCUS clusters and networks is dependent on many factors, other than the mere existence of CO_2 sources or storage capacities (Brownsort, 2020). Some of those factors are technical in nature, such as the possibility to develop optimized transport networks, the percentage of emissions that originate from industrial processes, the trending and profile of emissions in each facility, or as simple as the existence of space to build capture facilities, while others are concerned with social interactions with populations, stakeholders and between facilities owners or operators.

Detailed planning of CCUS clustering and network development in the promising regions, requires that STRATEGY CCUS conducts detailed inventories of those social and technical conditions in each region. While the social characterisation is conducted in WP3 -Social acceptance: stakeholder mapping and engagement - and presented in several Deliverables of STRATEGY CCUS, this report summarises the key technical data collected by local teams to characterise the conditions in each promising region. The actual data is not presented in this report, and instead will integrate Deliverable D2.4 of STRATEGY CCUS.

The technical characterisation in which local teams engaged was driven by guidelines produced early in STRATEGY CCUS timeline, in Brownsort (2020), which concentrates on methodologies for characterisation and definition of Industrial CCUS clusters and transport systems, and in Cavanagh et al. (2020), which addresses guidelines for storage resource assessment. Although a brief description of those methodologies is provided in this report, the interested reader should refer to the mentioned publications for detailed information.

[1] In this report Power generation, including combined heat and power (CHP) or co-generation, are included in the general meaning of "industry" whether such facilities are dedicated to particular industrial sites or supplying to grid distribution.

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While the guidelines and best-practices presented in those reports provided the general methodologies, they also acknowledged that each of the regions to characterise have their own particularities and several degrees of freedom were left in the methodologies for the local teams to make decisions and adapt the methodologies based on local conditions.

This report is organised as follows: chapter two contains the brief description of the methodologies and tools used by local teams and includes a short clarification of the terminology used in this report. Chapter three presents an overview of the main features of the eight promising regions, while chapter 4, the bulk of this report, summarises the key technical data for each region and is accordingly organised in eight sub-chapters. Chapter five presents conclusions and recommendations.

Two appendices are an integral part of the report. Appendix I is composed by maps for containing for each region information about: i) a map with the location and main features of the sources; ii) a map with the main features of the storage sites, and; iii) a map indicating the main features relevant for defining collection and transport networks. Interactive web maps with the main features were also produced and are accessible to the STRATEGY CCUS consortium.

Appendix II comprises a list of the attributes of the database completed by the local teams for each promising region. This list is included in this report as an indication of the data available to complete this report, but the actual data is not included here and will compose the databases to be presented as Deliverable D2.4.

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2 Approach to assess the technical potential of promising regions

The technical potential for implementing CCUS in the promising regions was assessed on the basic premise that Industrial CCUS clusters provide synergies, either in the capture facilities, at the transport networks or at injection and storage facilities, that result in decreasing costs for implementing the technology. However, the literature review conducted in Brownsort (2020) indicated that, often, there are slight differences in the terminology used when planning or revising CCUS infrastructures. It is, therefore, important to clarify some terms used in this report when describing the technical potential of each region. Figure 2-1 aims at providing a schematic illustration of the components of an Industrial CCUS cluster.

An **industrial capture cluster,** hereafter referred simply as "cluster" or "ICCUS cluster", is a geographical grouping of CO_2 emitters with potential to cooperate and build synergies to implement CO_2 capture. Depending on the spatial arrangement of sources in the promising region, more than one cluster may be an adequate solution for a given promising region.

The industrial CO_2 sources in the cluster are assumed to have the potential to implement, if they do not exist yet, **capture facilities** to separate CO_2 from the flue gas stream. Given the current development stage of capture technologies, it was assumed that each CO_2 source would have to build its own dedicated capture facility, except where more than one industrial source of the same type exist in very close proximity (such as, for instance, two glass factories using the same technologies and installed in the same industrial complex).

A CO_2 **collection infrastructure** is shared within the cluster to bring the CO_2 from each capture facility to a consolidation point, a **hub**. The collection network can, in general, be composed by a pipeline system, but for very small-capacity sources, the collection network can be composed by a modular system including road truck, rail tank-car, shipping or barge transport on inland waterways. The capacity of existing road tankers is typically up to 30 tons of CO_2 per truck, while for rail tank-car is normally on the order of 60 tons per each rail tank-car. River barges have also been used, with a capacity of up to 1500 t per ship (Santos, 2012).

The CO_2 **utilisation opportunities** are here regarded as those uses with a clear mitigation impact, either with a greenhouse gas contribution or that clearly enable other low-carbon actions, leaving out those technologies that have negligible impact (Cavanagh et al. 2020). Transport of CO_2 to the utilisation facilities can originate from the capture facility or from a hub, depending on the distance to the utilization site and the volumes expected to be used. Transport for utilisation purposes in many instances can be made by road or rail tanker or river barge, if the volumes required at the utilisation site are small. Obvious exceptions are large scale uses, e.g. for EOR purposes, where transport by pipeline from the hub may be more adequate.

At the hub, that collects all the CO_2 captured in the cluster, conditioning facilities (e.g. compressing, liquefaction, etc.) prepare the CO_2 for **trunk transport** by pipeline or ship to the injection and storage site where further reconditioning of the stream may be necessary. The available **geological storage capacity** and its distribution with respect to the sources, may result in scenarios where more than one cluster is developed in the promising regions, or more than one trunk transport solution may be necessary in different phases of the network development.

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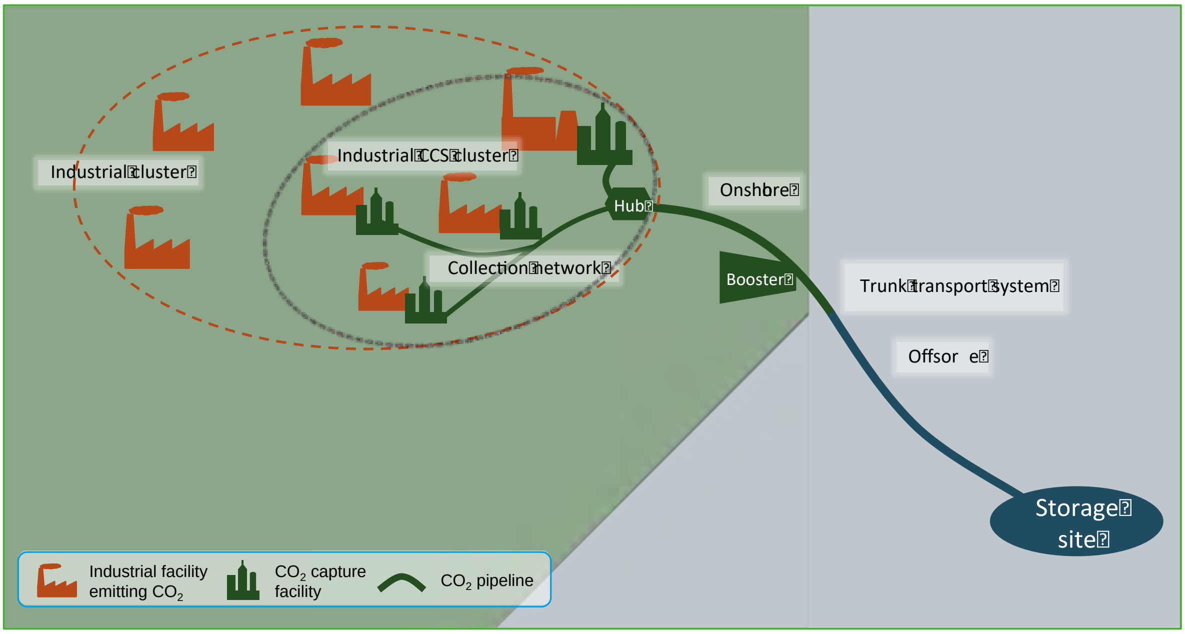

Figure 2-1 Schematic of ICCS cluster using pipelines for transport (Brownsort, 2020).

2.1 Methodology

The methodology for definition of clusters and transport systems is described in detail in Brownsort (2020) and is based on three questions, defining (Figure 2-2):

- WHAT CO_2 will be captured?
- HOW will this CO_2 be captured, collected, transported?
- WHERE will this CO_2 be stored?

Although not initially addressed in the methodology in Deliverable D2.1 of STRATEGY CCUS, a further question was added to cover for CO_2 utilisation:

- WHICH CO_2 utilisation technologies?

Determining what CO_2 may be captured

The objective is to develop an understanding of the CO_2 that may be captured in the cluster area as part of an industrial emissions reduction programme using CCUS. The starting point was the definition of current CO_2 emission quantities in the cluster area, the locations of emitters and related details. Distinctions between the fossil fuel combustion emissions, biomass emissions and process emissions were done whenever there was sufficient information.

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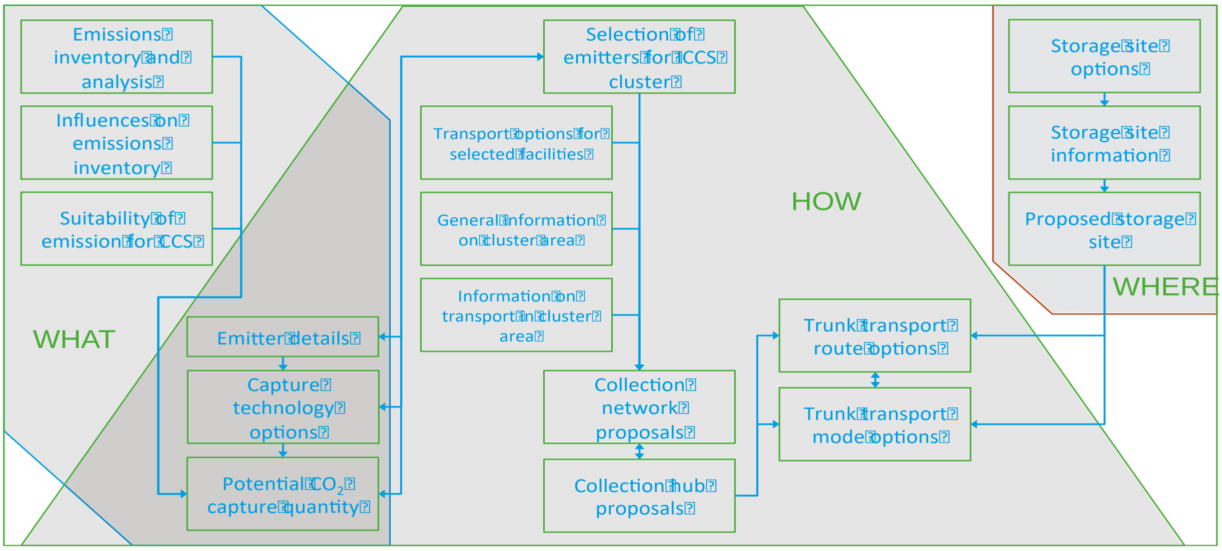

Figure 2-2 Outline of relationships between main steps of methodology. The three shaded areas highlight the three general steps WHAT, HOW, WHERE. The area of overlap, mid-left, represents information related to the second step, but specific to each emitter considered (Brownsort, 2020).

Once this inventory of the CO_2 emissions has been established, it was necessary to consider what portion of that would be appropriate to address using CCS. This was done taking into account foreseeable influences such as the development of alternative decarbonisation technologies, trend of evolution of emissions[2], economic factors, changes in societal behaviour, policy and markets (Table 2-1). Consequently, information on these issues was collected for each of the CO_2 sources inventoried.

Once a picture was developed of the quantity and sources of CO_2 emissions in an industrial area that may be addressed by CCS in the foreseeable future, the recognition of a promising ICCUS cluster took into consideration the CO_2 emitters that may participate in the CCS cluster and the CO_2 capture options for these sites. This needs to consider both the more technical aspects such as facilities involved, infrastructure, technology and routing decisions, and also some aspects of stakeholder involvement and interaction.

The spatial arrangement of the sources and the possibility that a consolidation hub could be implemented was a key aspect to delimit the cluster and to define the collection network possibilities. The identification of existing pipeline routes and corridors, roads and railway terminals, as well as possible waterways transport, was essential to identify situations in which modular transport could be interesting.

Table 2-1 Lists of options for classification of sector, trends, trend driver and decarbonisation alternative.

[2] The trend of emissions at each facility was defined taking using the reported CO_2 emissions to the third-phase of the EU-ETS, from 2013 to 2018.

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Industry Sector	Emission trend	Trend driver	Decarbonisation alternative
Power	Stable	Consumer behaviour	Energy efficiency
Ammonia	Growing	Competition	Material efficiency
Cement	Falling	Policy	Electrification
Ethylene	Closing	Regulation	Fuel switch to biomass
Ethylene Oxide	Irregular	Innovation	Fuel switch to biogas
Hydrogen	Periodic	Other	Fuel switch to hydrogen
Iron & Steel	Seasonal	Unknown	Other
Chemicals (other)		Other	
Refineries			
Oil & gas Processing			
Paper and pulp			
Non iron metals			
Glass			
Food & drink			
Fermentation			
Energy from waste			
Anaerobic digestion			
Water/sewage treatment			
Other			

Determining how CO_2 will be captured, collected and transported

The location of proposed CO_2 storage sites usually constrained the options for trunk transport, for the most part considering only the possibilities of pipeline or ship transport for offshore storage. In fact, the location of the storage site also influenced the definition of the capture cluster itself, as the location of the hub, design of the collection network, and ultimately the capture facilities that integrate one cluster are a function of the storage capacity available in a particular site.

Determining the technologies for CO_2 utilisation

The role of carbon capture and utilisation in industrial decarbonisation is less clear than geological storage, since some utilisation processes lead to permanent removal of CO_2 from the atmosphere through its incorporation in stable products, while with other processes the CO_2 utilised is re-released in periods ranging from days to a few years.

The framing of CO_2 utilisation in STRATEGY CCUS is technologies with a clear mitigation impact having a negative greenhouse contribution, or technologies which will improve the business model of the CCUS chain or promote the circular economy around the CO_2.

Cavanagh et al. (2020) proposed some questions to help frame which utilisations may, in each STRATEGY CCUS promising region, contribute to a clear mitigation impact.

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Table 2-2 CCUS mitigation framing and storage assessment for utilisation technologies (Cavanagh et al., 2020)

Question	Criteria	Framing Question
1	Quantity in	How much captured CO_2 is used per unit of production?
2	Quantity out	How much CO_2 is emitted per unit of production?
3	Scale	How many units will be produced per year?
4	Storage rate	How much of the used CO_2 will be stored per year?
5	Impact	Does the storage rate exceed the emission rate?
6	Permanence	How long will the CO_2 be stored for?
7	Accounting	How will storage be monitored and verified?
8	Other	How else does the technology mitigate emissions?

A pre-set list of CO_2 utilisation technologies was adopted from the IEA (2019) report " Putting CO_2 to Use", leaving out those technologies that have negligible impact (food and beverages, medical uses, welding, fire suppression, dry Ice, decaffeination, dry cleaning). Furthermore, and to fully cover possible uses indicated in national and regional plans and roadmaps, some utilisation not listed in IEA (2019), such as Enhanced Geothermal Systems (EGS) and Enhanced Coal Bed Methane (ECBM), were included as possibly interesting for some of the STRATEGY CCUS regions.

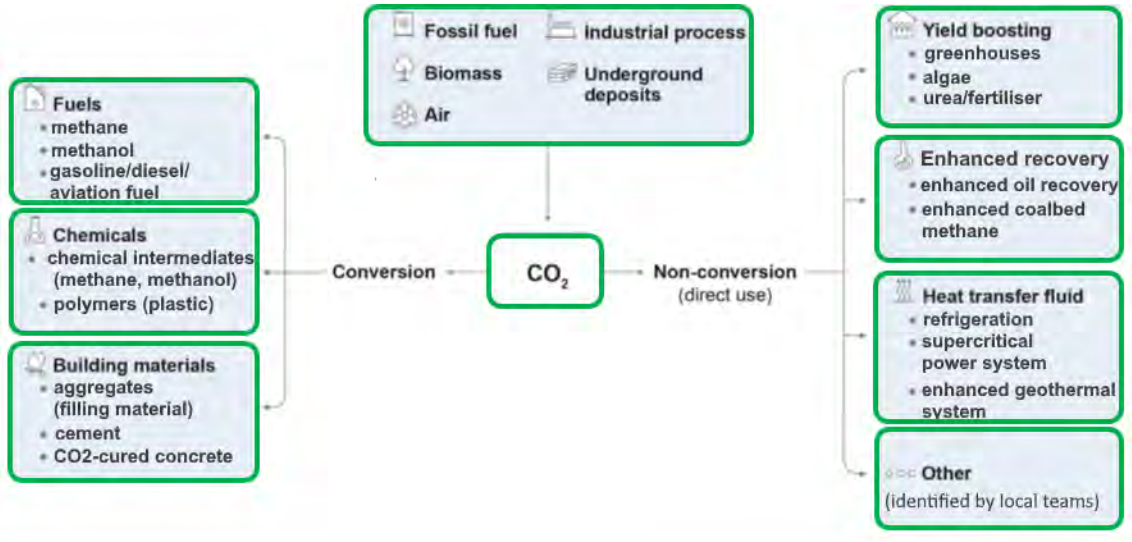

Figure 2-3 Simple classification of pathways for CO_2 utilisation (adapted from IEA, 2019).

Determining the CO_2 storage opportunities

For a developing ICCS cluster to achieve its main intended purpose of decarbonising industry in an area, options that provide a permanent sink for the captured CO_2 need to be defined in parallel, to allow creation of an integrated capture, transport, utilisation and storage chain.

Specific guidelines were developed to assess storage resources in the promising regions, including the definition of the storage site locations, capacity and injectivity estimates, and confidence levels

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on those estimates. The guidelines focus on three reservoir types, Deep Saline Aquifers (DSA), Depleted Hydrocarbon Fields (DHF), including the expectation for EOR, and Uneconomic Coal Beds (UCB).

Deliverable D2.3 of STRATEGY CCUS will detail the storage capacity resource assessment for each of the areas, and this report refers only to the location of the storage sites and their capacities, as these influence the development of the collection and transport networks. We refer here also to the TIERS in the pyramid approach followed in Cavanagh et al. (2020):

*"resource assessment is two-fold: a qualitative suitability appraisal that supports the capacity estimate. Suitability covers all technical aspects of storage from reservoir capacity and quality to seals, faults and wells. The appraisal consists of a Boston square score for both attribute suitability (y-axis) and data quality (x-axis). Each attribute is plotted to provide an overview of the site and data gaps that may need addressing (*Figure 2-4*, right).*

*The capacity estimate is a quantitative resource pyramid approach consisting of four tiers that reflect the increasing maturity of data and understanding about potential storage capacity from regional first approximations to targeted storage site candidates. The requirements for each tier reflect this maturation. The described tiers are compatible with existing schemes (CSLF TERR, SPE SRMS), allowing outcomes to be transferred to equivalent classifications if required (*Table 2-3 *and* Figure 2-4*).*

Table 2-3 Tiers for storage resource assessment

Tier 1	Regional assessment; equivalent to Prospective (Theoretical),	Generic SEFs (storage efficiency factor). Formation and storage unit estimate. First approximation. Low data burden and global storage efficiency values where boundary conditions are poorly constrained or uncertain.
Tier 2	Discovery assessment; equivalent to low Contingent (Effective),	Tailored SEFs. Daughter unit estimates. Second approximation. Moderate data burden and lithology specific regional storage efficiency factors. Distinction between deep saline aquifers, depleted hydrocarbon fields and coal beds. Boundary conditions are established.
Tier 3	Prospect assessment; equivalent to Pending/On Hold (Practical),	Detailed data prospective candidates. Third approximation with a more taxing data burden, including sub attributes of the main factors used to estimate capacity and lithology specific local SEFs. Each candidate prospect requires either existing or targeted data acquisition sufficient to build a simple geomodel for first pass simulation and well location consideration.
Tier 4	Site assessment; equivalent to Justified/Approved/On Injection (Matched), project.	Targeted storage sites. The final approximation prior to operation. This has the highest data burden and requires a detailed geomodel for reservoir simulation studies. Outcomes from the simulations test the accuracy of the storage efficiency factors and provide scenarios for maximising capacity based on well planning and scheduling.

The tier and BSA of each storage unit are discussed and revised in Deliverable 2.3, but the definition of transport networks must take into account the tier of each storage opportunity. In this report we refer to the tier defined for each storage unit at the time of data collection, before the analyses conducted in Deliverable D2.3, which can result in new storage capacity estimates and tier assignment.

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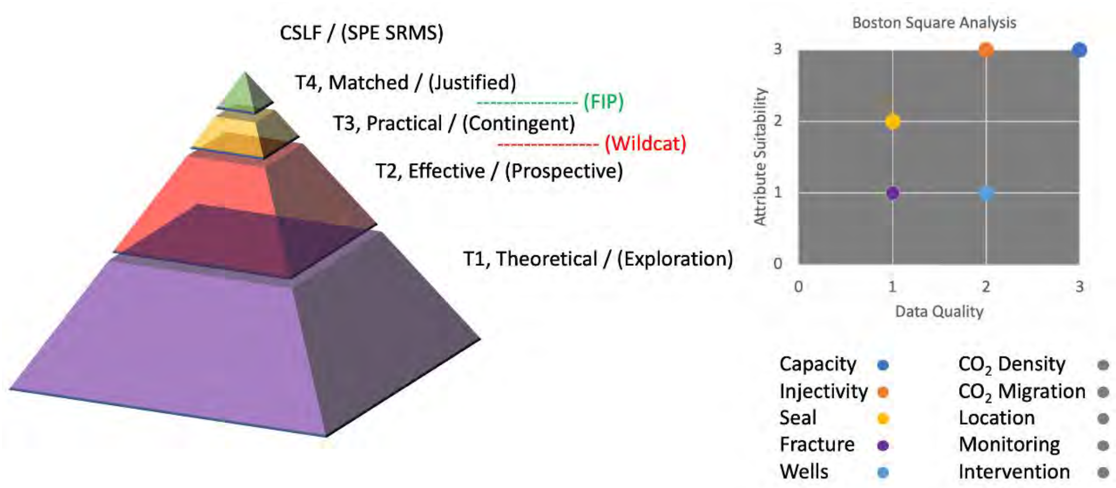

Figure 2-4 Left: Four-tier capacity pyramid with CSLF and SRMS terminology; right: Boston square analysis (Cavanagh et al., 2020).

2.2 Characterising the potential for ICCUS development

Brownsort (2020) proposed a list of features that can be used to describe potential ICCUS clusters, based on general knowledge of existing and proposed ICCUS clusters. The list was suggested as a structure for considering the strengths and weaknesses of different clusters, to reflect on their relative positions. This approach describes potential clusters in terms of six groups of features: i) emissions; ii) the area; iii) the industries; iv) relationships, v) infrastructure and vi) CO_2 storage.

This list of features will be used in this report when describing the promising regions in chapter four, not as means of comparing them, but to identify the strengths and weaknesses. It is recognised, however, that the group “Relationships”, composed of the following features:

- Stakeholders – are key stakeholders recognised, engaged, supportive?
- Policy position – is local and/or national policy supportive?
- Public position – is local population engaged with industry, positively or negatively, e.g. employment or air quality issues?

relates to social aspects, rather than technical conditions, and therefore will not be addressed here. Table 2-4 presents and describes the features included in each of the other five groups.

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Table 2-4 List of features to describe potential ICCUS clusters

GROUP	Feature/ factor	Comment for cluster
EMISSIONS	Emission location distribution	How closely "clustered" is the area, are there few or many vents at facilities?
	Emission volume distribution	Are there "anchor" emitters, several large emitters, many small emitters?
	Emission volume profile	Are facilities at risk/closing, or is investment occurring, is there seasonal variation?
	Emissions type and quality	Are there significant process emissions, are there high-concentration emissions, are there problematic contaminants?
AREA	Industrial area character	Is it urban or remote, large or small, spread out or dense?
	Importance of industry	Is the area predominantly industrial, is industry main employer in area?
	Cluster recognition	Is there an existing cluster mentality, history of cluster focus, existing study results?
INDUSTRIES	Integration of industry	Is there a common culture, cross-industry bodies, service interdependence, sharable resources etc?
	Decarbonisation alternatives	What scope/feasibility for energy efficiency, electrification or biomass, hydrogen?
	CCU	What potential for CCU, is it "defining" e.g. EOR demand or syngas availability?
	Motivation for decarbonisation	Will industry prioritise decarbonisation?
	Motivation for CCS	Can industry gain from CCS?
INFRASTRUCTURE	CO_2 collection options	Are there existing pipeline corridors, rail links, liquid-CO_2 (L-CO_2) terminals, are there geographic or other constraints on routes for collection?
	CO_2 consolidation options	Are sites for consolidation hubs available, e.g. For buffer storage, central processing, compression or liquefaction?
	Existing CO_2 infrastructure	Are there any existing capture, transport or utilisation operations or experience?
	Infrastructure reuse options	Are there relevant existing pipelines, ports, terminals?
STORAGE	Storage accessibility	Is area close to known potential CO_2 storage sites?
	Storage capacity	Is accessible storage of suitable capacity, injectivity, security?
	Storage flexibility	Are there alternatives to primary storage site?
	Storage development integration	Is there an organisation interested/capable of developing storage?

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3 Overview of emissions and storage capacities in the STRATEGY CCUS promising regions

The eight STRATEGY CCUS promising regions (Figure 3-1) have identified 174 industrial and power facilities with current CO_2 emissions that amount to 121.5 Mt/y. Not all sources are necessarily adequate for CO_2 capture, as some of those are implementing other decarbonisation initiatives or are being phased out, but this inventory provides the starting basis for considering implementation of CCUS networks in each region.

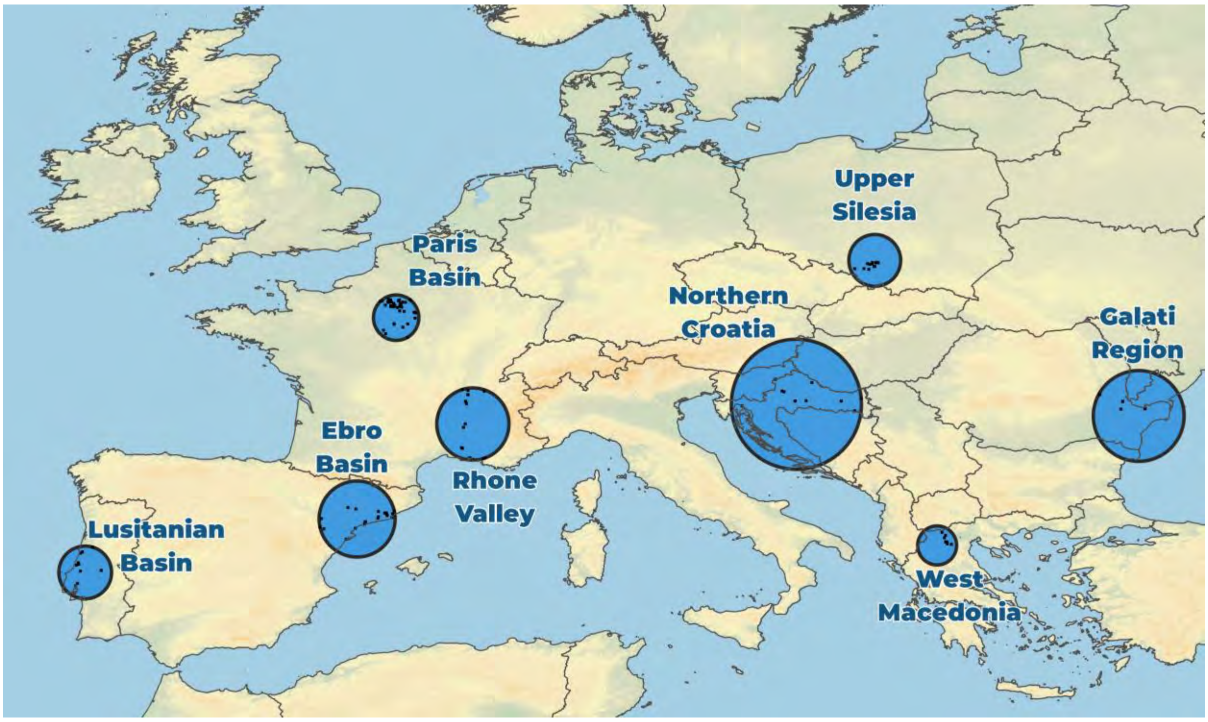

Figure 3-1 STRATEGY CCUS Promising regions.

Power plants, including biomass and CHP plants, are the most important sector, both in terms of number of facilities (59) and in emissions, being responsible for 57% of all CO_2 produced in the regions (Figure 3-2). Nonetheless, the sector is not the most carbon intensive in the study regions (and its importance is set to decreases as several power plants are set to shut down in coming years), since the Iron & steel sector facilities, although being only nine, are responsible for 17.1 Mt/y, 14% of all emissions. Cement factories is the only other sector that emits more than 10 Mt/y in the promising regions, with all other sectors with an impact of less than 4% to the total emissions.

Although less carbon intensive, there is a considerable number of facilities in the "Energy from Waste" sector (26 facilities) and in the "Chemicals (other)" sector (12 facilities) (Figure 3-2).

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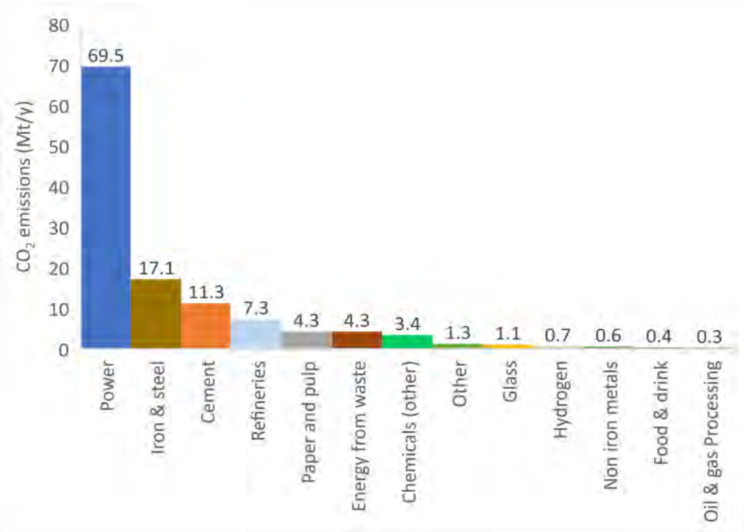
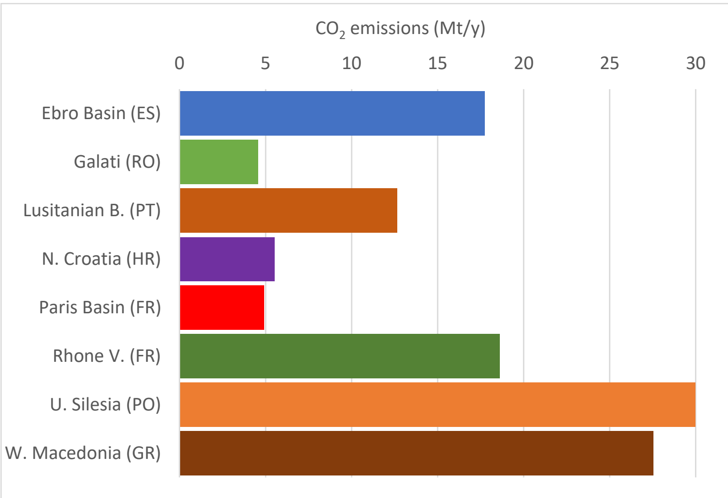


Sector	Facilities	CO_2 emissions (Mt/y)
Power	59	69.5
Cement	23	11.3
Paper and pulp	8	4.3
Glass	10	1.1
Refineries	7	7.3
Other	6	1.3
Oil & gas Processing	1	0.3
Energy from waste	26	4.3
Food & drink	6	0.4
Iron & steel	9	17.1
Chemicals (other)	12	3.4
Non iron metals	4	0.6
Hydrogen	3	0.7
TOTAL	174	121.5

Figure 3-2 CO_2 emissions and number of facilities per sector in the promising regions.

Upper Silesia and West Macedonia are the promising regions with the highest emissions, together emitting 57.5 Mt/y, nearly has much as the six other promising regions, despite having a relatively low number of sources (Figure 3-3). This asymmetry is explained by the coal power plants that still exist in those coal producing regions.

Considering all other industrial sectors, the Rhone Valley and the Ebro Basin are the most industrialised areas (Figure 3-4), with simultaneously the higher number of emitters, carbon intensity and diversity of industrial sectors. The Paris Basin, in spite of a large number of facilities, is one of the region with lowest emissions, since many of the facilities are in the ”Energy-from-Waste” sector and in the low carbon intensity “food & drink” sector.



Region	Facilities	CO_2 Emissions (Mt/y)
Ebro Basin (ES)	26	17.7
Galati (RO)	8	4.6
Lusitanian B. (PT)	20	12.7
N. Croatia (HR)	12	5.5
Paris Basin (FR)	40	4.9
Rhone V. (FR)	48	18.6
U. Silesia (PO)	13	30.0
W. Macedonia (GR)	7	27.5

Figure 3-3 CO_2 emissions and facilities distribution in the promising regions.

The cement sector plays an important role in the Ebro basin, Lusitanian basin and Rhone Valley promising regions, and their relative importance is set to increase at least for the former two regions, since it possesses less decarbonisation alternatives than the power plants that currently dominate the emission spectrum in Spanish and Portuguese regions. The paper & pulp sector is a

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significant emitter in the Lusitanian basin, with five facilities emitting 3.41 Mt/y, although the vast majority from biomass combustion. Although carbon neutral, this intensive use of biomass can create the opportunity for negative emissions through BECCS.

The iron & steel sector is particularly important in the Rhone Valley, where it is the main emitting sector, and in the Galati region, although in this case a single iron & steel mill is responsible for more than 90% of the total emissions in the region.

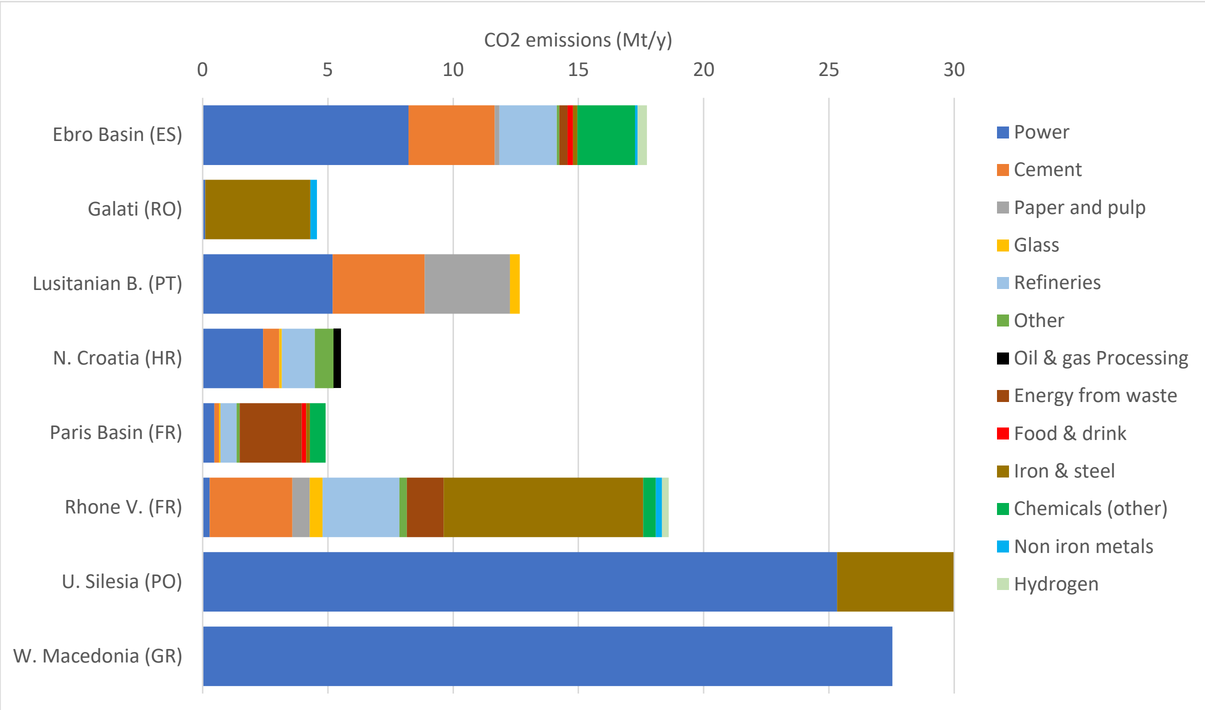

Figure 3-4 CO_2 emissions per sector in each promising region.

The average estimated storage capacity in the eight promising region totals more than 7.7 Gt, the bulk being deep saline aquifers, which represent 95% of the available capacity. Depleted Hydrocarbon Fields provide an added capacity of 240 Mt, while Hydrocarbon fields currently being exploited and with theoretical possibilities to implement CO_2-EOR have an estimated storage capacity of 144 Mt. Uneconomic Coal Beds have very small capacity (Figure 3-5).

Although the offshore capacity is considerable, 3.8 Gt, it is almost exclusively concentrated in saline aquifers the Lusitanian basin, with a minor amount (16.7 Mt) in the Galati Region, and is of Tier 1, with a much higher uncertainty on the resource estimates than for the onshore storage in the same regions.

The uncertainty related to the assessment tier is reflected in the resource estimates, with the offshore in Portugal and onshore West Macedonia, Upper Silesia and Northern Croatia estimates for deep saline aquifers being at the lowest tier (Figure 3-6) and, thus, very likely to be revised to lowest figures as the assessment progresses in the resource pyramid.

On the contrary, the depleted hydrocarbon fields are by definition at least Tier 2, with a much higher confidence level, and providing priority storage opportunities for the Paris Basin and Galati Region (and Northern Croatia as the producing hydrocarbon fields start getting depleted).

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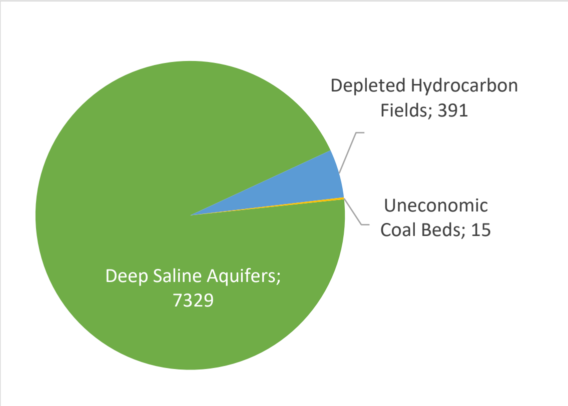
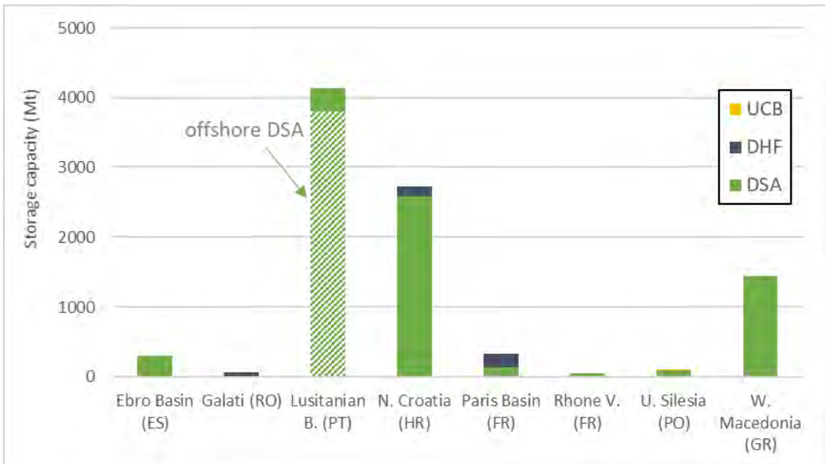


Storage type	Storage units	Storage capacity (Mt)
Deep Saline Aquifers	77	7329
Depleted Hydrocarbon Fields	66	391
Uneconomic Coal Beds	2	15
Total	145	7736
Setting	**Storage units**	**Storage capacity (Mt)**
Onshore	124	3924
Offshore	21	3812

Figure 3-5 Estimated storage capacity per reservoir type in the promising regions.

Still, it is also clear that some regions have very limited storage capacity, such as in Upper Silesia, where Tier 1 deep saline aquifers and uneconomic coal beds provide only 112 Mt capacity, and in the Rhone Valley, where Tier 2 Deep Saline Aquifers amount only to 57 Mt of storage capacity.

Northern Croatia and Galati Region show potential for utilisation of CO_2 in EOR processes, and that could in fact be the main initial focus for CCUS deployment in those regions as the needs for CO_2 capture may not be as large as in other regions and be met by the demand for CO_2-EOR.



Region	DSA	DHF	UCB
Ebro Basin (ES)	299		
Galati (RO)	17	55	
Lusitanian B. (PT)	3795		
N. Croatia (HR)	2585	144	
Paris Basin (FR)	141	192	
Rhone V. (FR)	57		
U. Silesia (PO)	96		15.3
W. Macedonia (GR)	1443		

Figure 3-6 Storage resources estimates distribution in the promising regions.

It is not expected that the 172 sources inventoried in the STRATEGY CCUS promising regions will join CO_2 capture clusters (as said, some of the most important sources are in fact scheduled for closure) and the storage capacity estimates (particularly for deep saline aquifers) will decrease as the assessment rises in the Resource Pyramid. Still, even at this early stage, the ratio of inventoried storage capacity to the current CO_2 emissions in each promising region, will allow to identify potential deficits in the storage capacity.

Figure 3-7 depicts that ratio. If the CO_2 capture scenarios in the Rhone Valley and in Upper Silesia approach even a limited fraction of the current emissions, there will not be enough capacity to store that CO_2 in local geological formations. Even for the Ebro Basin, one of the most significant industrial

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regions in STRATEGY CCUS, where the storage capacities were assessed at Tier 2, there may be considerable constraints to CO_2 storage if the capture rate approaches that of the current emissions.

CO_2 utilisation technologies, with an impact to climate change mitigation as defined in Figure 2-3, is incipient at every promising region, except for the CO_2-EOR activity ongoing in Croatia. Therefore, rather than identifying ongoing activities, local teams identified those CO_2 utilisation technologies: i) that are included in national roadmaps and strategic documents as relevant for each country; ii) with a high Technology Readiness Level (TRL) in which research is being conducted in each region; iii) having an impact on the business model, as CO_2-EOR, synthetic natural gas and greenhouse crops, as one important barrier for CCUS deployment is economic.

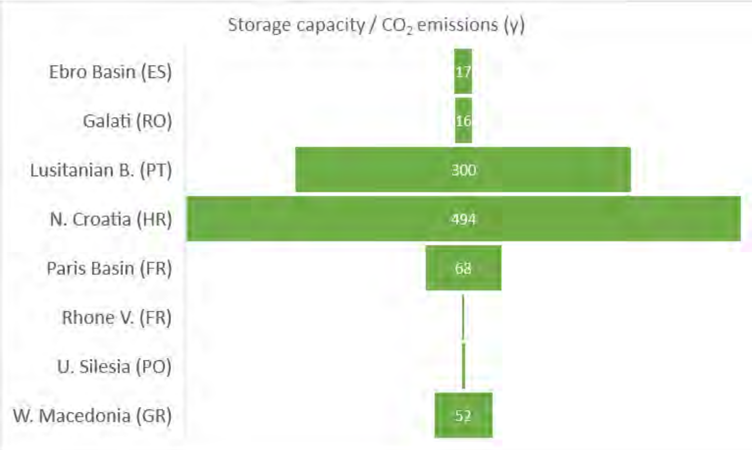

Figure 3-7 Ratio between storage capacity estimates and current CO_2 emissions in each promising region.

Table 3-1 CO_2 utilisation technologies with perspectives for implementation at each promising region, according to national roadmaps, strategic documents and ongoing research.

Region	Utilisation technology*
Ebro Basin	Chemistry and synthetic fuels Building materials / carbonation Algae Heat transmission fluid in the cement industry
Galati Region	CO_2-EOR
Lusitanian basin	Synthetic natural gas /Liquid hydrocarbons Building materials / carbonation Greenhouses
Northern Croatia	CO_2-EOR Synthetic fuels and methane
Paris Basin	Greenhouses EGS Fertilizer production
Rhone Valley	Chemical products Synthetic fuels Algae Building materials / carbonation
Upper Silesia	Synthetic natural gas Chemical products
West Macedonia	Building materials / carbonation Polymers (plastics, resins, foams) Greenhouses Fertilizer production

*Only considering technologies with a meaningful impact to climate change mitigation (see Figure 2-3, page 21).

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4 Technical potential of promising regions

The data gathered for each promising region aimed at providing the technical basis on capture, transport, utilization and storage conditions, for assessing the viability of defining and implementing CCUS clusters in each promising region. Information was collected by local teams and implemented in a database that constitutes Deliverable D2.4. Furthermore, a uniform methodology to classify storage capacities maturity levels and confidence was implemented and is described in Deliverable D2.3, together with an analysis of the storage capacity and tier for each promising region.

This chapter builds on the information collected in the database to present the key data for each region about:

i. Emissions and sectors, focusing on those which the local teams found with possibilities for implementing CO_2 capture;
ii. Storage capacity, a high-level analysis considering only the estimates provided by local teams based on previous projects and studies, but updated values will be included in D2.3, to be released in month 18 of STRATEGY CCUS;
iii. Spatial conditions for network development, considering the geographic distribution of source and sinks and the transport opportunities;
iv. CO_2 utilization options, addressing only those ongoing or planned activities which can have a meaningful impact in CO_2 emissions reduction or in the business model;
v. Potential for ICCUS development, considering the list of features for cluster characterisation suggested by Brownsort (2020) and presented in section 2.2.

Work Package 5 (WP5) in STRATEGY CCUS will develop scenarios of ICCUS networks in each region. Local teams provided a preliminary vision of what clusters and hubs may be realistic in each region and these will be discussed here as a basis for the scenarios to be built in WP5. The clusters and hubs suggested by the local teams take only into account the spatial conditions for the ICCUS cluster and do not consider economic aspects (which are part of WP5).

The description of technical potential in each region, in sections 4.1 to 4.8, refers to the sources and sinks in each region by the Facility Name and ID code used in the STRATEGY CCUS databases. The Facility Name is maintained as it appears databases that compose Deliverable D2.4. The ID code is in the form *XX.ES.YY* and *XX.SU.YY*, where XX is the country code in the International Naming Convention (given that there are two region in France, FR1 is used for the Paris Basin and FR2 for the Rhone Valley), ES is *Emission Source* and SU is *Storage Unit* and YY is the number of order of the source or sink in each region. This referencing system is maintained in the tables throughout this chapter but in figures and maps (in appendix) only the number of order is used, since the figures and maps are already indicating the region and legends are used to refer to sources or to sinks.

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4.1 Ebro basin – Spain

4.1.1 Emissions and industry sectors

The Ebro basin inventory comprises twenty-six industrial facilities emitting more than 0.1 $MtCO_2$/y, and totalling emissions of 17.74 Mt/y in 2017. Power plants, cement and chemical factories are the dominating sectors, both in the number of facilities, and in emissions, accounting for 79%. There is a single refinery (SP.ES.26), at Tarragona, but its 2.29 Mt/y emissions make for 13% of the total emission in the region. All other industrial sectors are represented by a single facility, and together emitted 1.49 Mt/y (Figure 4-1).

The "Endesa Generación" coal power plant (SP.ES.1) in Andorra, emitting 4.81 Mt/y is the largest emitter in the region, but the facility is set to shut down still during 2020, making the Repsol refinery at Pobla de Mafumet (SP.ES.26), Reus, the most important emitter in the Ebro Basin. There are three other facilities emitting more than 1 Mt/y, notably two cement plants, "Cementos Molins Industrial (Sant Vicenç Dels Horts)" (SP.ES.2) and "Cementos Portland Valderrivas (Santa Margarida I Els Monjos)" (SP.ES.3), both in the Barcelona outskirts, and the chemical plant of "Dow Chemical Iberica (Dow Nord)" (SP.ES.4) at Reus.

There are other important sources emitting in the range 0.5 to 1 Mt/y, most of them located in the industrial areas of Barcelona and Reus, with the level of emissions usually decreasing for sources located further way from these two industrial areas, the exception being the Cement plant (SP.ES.7) at Alcanar (0.78 Mt/y).

There are no high CO_2 concentration sources in the region.

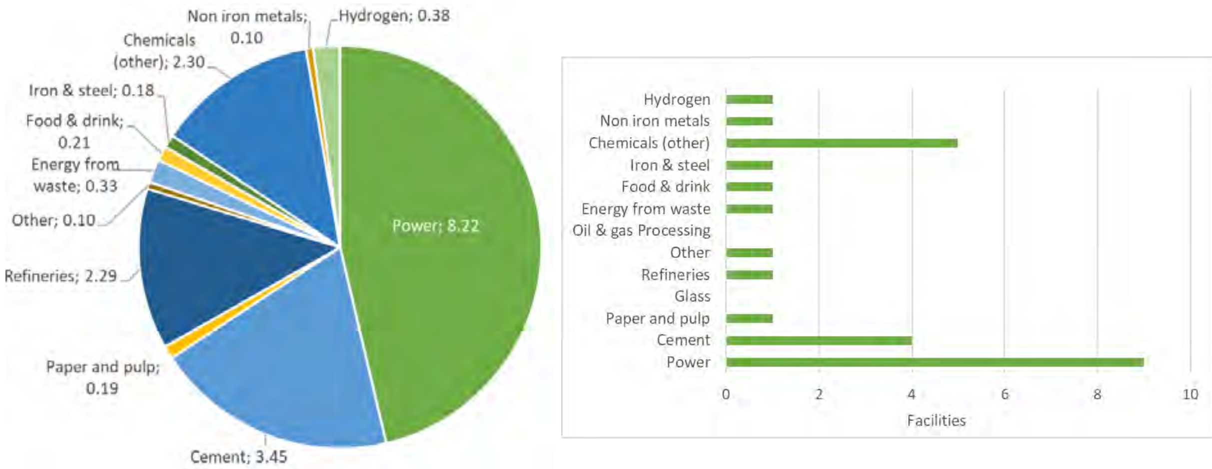

Figure 4-1 Emissions (in Mt/y) and facilities per sector in the Ebro basin in 2017

In the event that the shutdown of the Andorra coal power plant is confirmed, the CO_2 emissions in the Ebro basin will reduce significantly, a trend that will be aided by the reductions in the cement sector, as three out of the four cement plants in the region are showing a downward trend in the CO_2 emissions, with "consumer behaviour" identified as the main driver (Table 4-1).

This decrease in emissions in the cement sector is not a generalised trend for the other sectors, as the majority of sources are experiencing a stabilisation or an irregular trend, and three facilities are

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even showing a growing trend; the natural gas power plant (SP.ES.5) “Sant Adrià de Besòs - grup 4”, the waste power plant “Planta de valoritzacio energetica de Sant Adria De Besos” (SP.ES.15) and the chemicals plant “Cales de Pachs, S.A.” (SP.ES.25).

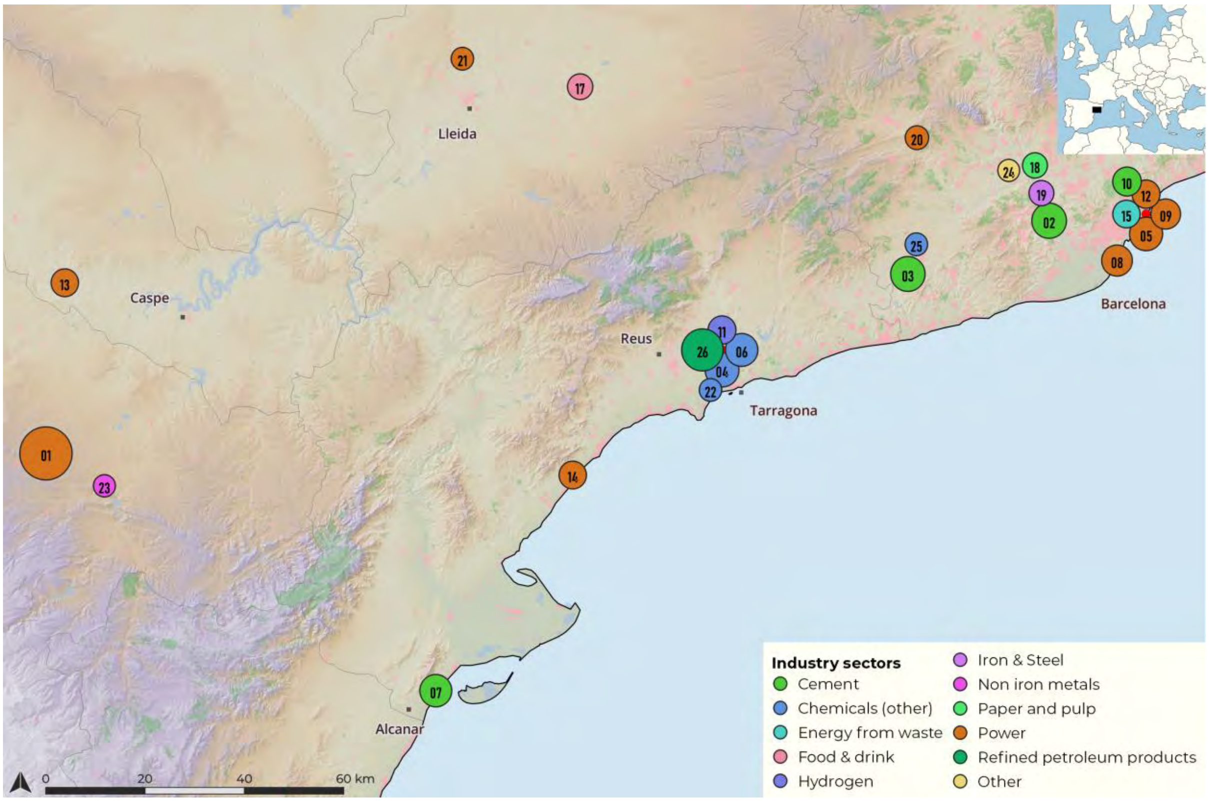
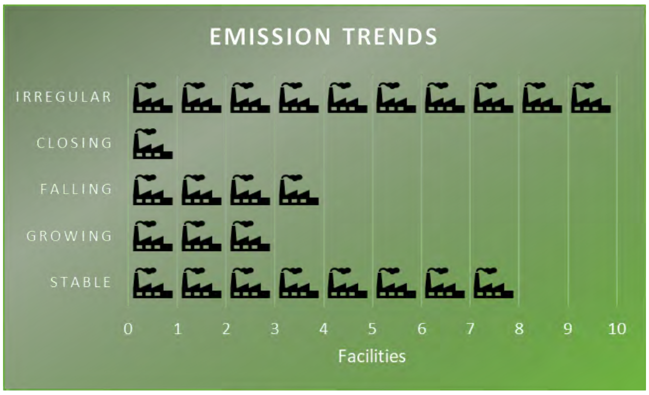


Figure 4-2 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-1. For detail see map in Appendix I.

Fossil fuel combustion is the main source of emissions. The Endesa power plant in Andorra, Teruel, due to be closed in 2020, used coal as the primary fuel (Table 4-1), but natural gas is the main fuel utilised in fifteen of the 26 facilities, while coke and petcoke is the main fuel used in six facilities (Table 4-1). Refinery and petrochemical gas and other gaseous fuels are being used in three facilities (“Dow Chemicals”, “Repsol Química” and “Repsol Petróleos”).



Decarbonisation alternatives indicated for most facilities are energy efficiency, switch to biomass or to hydrogen, but alternatives are less obvious for those facilities in which process induced emissions are most relevant, making them more obvious targets for implementation of industrial CCUS plans. The cement plants are those where process induced emissions are most relevant, with 62% to 69% of the emissions not related to fuel combustion, but also the chemical plant “Industrias Químicas del Óxido de Etileno (La Canonja)” (SP.ES.22) may pose an interesting case for CO_2 capture, since process induced emissions are 46.7%.

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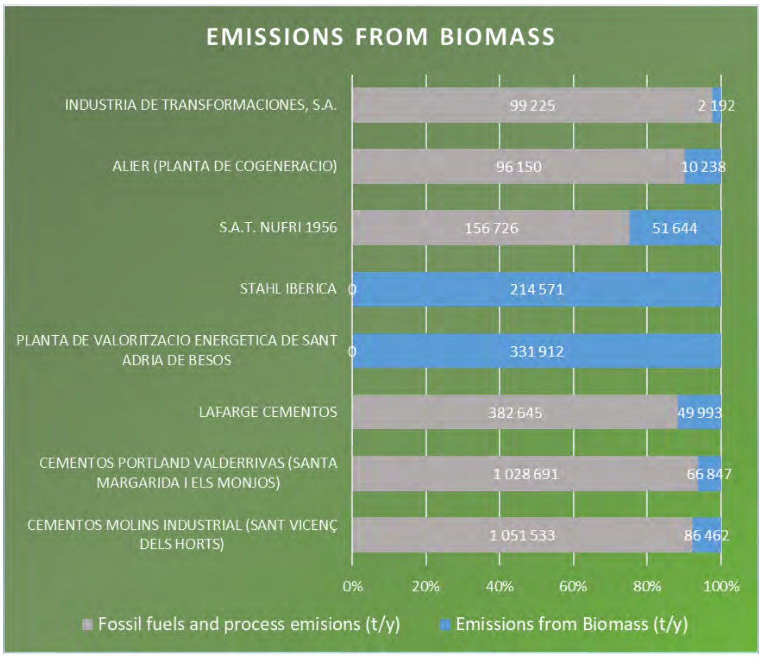
CO_2 produced from waste or biomass combustion is important in eight facilities, totalling 814 kt CO_2/y, and presenting possible interesting cases for BECCS where biomass and biogas are relevant energy sources, such as in the "S.A.T. NUFRI 1956" facility (SP.ES.17) of the food & drink sector and in the "Planta de Valorització Energètica de Sant Adrià de Besòs" waste processing facility (SP.ES.15).



The number of emission points in each facility is sometimes high, which can add challenges to the technical and economic feasibility of CO_2 capture, since fourteen facilities have more than three emission points, and in three facilities: Repsol Química (SP.ES.6), Cemex Española Operaciones (Alcanar) (SP.ES.7) and S.A.T. NUFRI 1956 (SP.ES.17) there are more than ten emission points.

4.1.2 CO_2 Storage possibilities

The geological storage opportunities in the Ebro Basin are provided by onshore deep saline aquifers. Twenty-one storage units in deep saline aquifers were identified, corresponding to Tier 2 resources and totalling a storage capacity of 299 Mt. Despite the proximity to the Mediterranean Sea, offshore storage sites were not included in the assessment due to data confidentiality issues. Still, there are three storage units near the coastline, units Ebro Delta 1 (SP.SU.3), Ebro Delta 2 (SP.SU.4) and Reus (SP.SU.28) but the vast majority of the storage capacity is provided by units located tens to more than 100 km from the coast where most of the CO_2 sources are located (Figure 4-3).

The total estimated storage capacity of 299 Mt compares to the current 12.93 Mt/y emissions from the operational sources (already discarding the Endesa power plant at Andorra). Given that assessments for Tier 3 and 4 will probably retrieve lower storage capacities and that meaningful impact requires that CCUS is implemented for decades, it is not obvious that the onshore geological formations in the Ebro basin can comfortably accommodate all the CO_2 that can be potentially be captured in the region.

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Table 4-1 Main features of CO_2 emitting facilities in the Ebro basin

Emitter ID	Facility name	Sector	Location	Emissions (tCO_2/y)	Emission trend	Main fuel
SP.ES.1	Endesa Generación, S.A.	Power	Andorra	4810192	Closing	Coal
SP.ES.2	Cementos Molins Industrial (Sant Vicenç Dels Horts)	Cement	Sant Vicenç dels Horts	1137995	Falling	Petcoke
SP.ES.3	Cementos Portland Valderrivas (Santa Margarida I Els Monjos)	Cement	Santa Margarida i els Monjos	1095538	Falling	Petcoke
SP.ES.4	Dow Chemical Iberica (Dow Nord)	Chemicals (other)	La Pobla de Mafumet	1027171	Irregular	Refinery and petrochemical gas
SP.ES.5	Central Termica De Cicle Combinat (Sant Adrià De Besòs - Grup 4)	Power	Sant Adrià de Besòs	926299	Growing	Natural gas
SP.ES.6	Repsol Quimica	Chemicals (other)	La Pobla de Mafumet	841202	Irregular	Other gaseous fuels
SP.ES.7	Cemex España Operaciones (Alcanar)	Cement	Alcanar	778988	Falling	Petcoke
SP.ES.8	Central Termica De Cicle Combinat (Port De Barcelona)	Power	Barcelona	643205	Irregular	Natural gas
SP.ES.9	Central Termica De Cicle Combinat (Sant Adrià De Besòs - Grup 5)	Power	Sant Adrià de Besòs	543193	Irregular	Natural gas
SP.ES.10	Lafarge Cementos	Cement	Montcada i Reixac	432638	Stable	Petcoke
SP.ES.11	Hyco (La Pobla De Mafumet)	Hydrogen	La Pobla de Mafumet	379621	Irregular	Natural gas
SP.ES.12	Central Termica De Cicle Combinat (Sant Adrià De Besòs - Grup 3)	Power	Sant Adrià de Besòs	378049	Irregular	Natural gas
SP.ES.13	Central De Escatron	Power	Escatrón	341214	Falling	Natural gas
SP.ES.14	Central De Ciclo Combinado Plana Del Vent	Power	Vandellòs i l'Hospitalet de l'Infant	338598	Irregular	Natural gas
SP.ES.15	Planta De Valoritzacio Energetica De Sant Adria De Besos	Energy from waste	Sant Adrià de Besòs	331912	Growing	Urban waste
SP.ES.16	Stahl Iberica	Chemicals (other)	Parets del Vallès	214571	Stable	Natural gas
SP.ES.17	S.A.T. Nufri 1956	Food & drink	Mollerussa	208370	Irregular	Natural gas
SP.ES.18	Barcelona Cartonboard	Paper and pulp	Castellbisbal	185012	Stable	Natural gas
SP.ES.19	Compañia Española De Laminacion (Celsa 1-4)	Iron & steel	Castellbisbal	184364	Irregular	Natural gas
SP.ES.20	Uficsa	Power	Pobla de Claramunt, La	129172	Stable	Natural gas
SP.ES.21	Alier (Planta De Cogeneracio)	Power	Rosselló	106388	Stable	Natural gas
SP.ES.22	Industrias Quimicas Del Oxido De Etileno (La Canonja)	Chemicals (other)	La Canonja	106214	Stable	Natural gas
SP.ES.23	Industria De Transformaciones, S.A.	Non iron metals	Calanda	101417	Stable	Coke
SP.ES.24	Seat	Other	Martorell	100787	Irregular	Natural gas
SP.ES.25	Cales De Pachs, S.A.	Chemicals (other)	Pacs del Penedès	106376	Growing	Petroleum coke
SP.ES.26	Repsol Petróleo S. A.	Refineries	La Pobla de Mafumet	2290416	Stable	Refinery and petochemical gas

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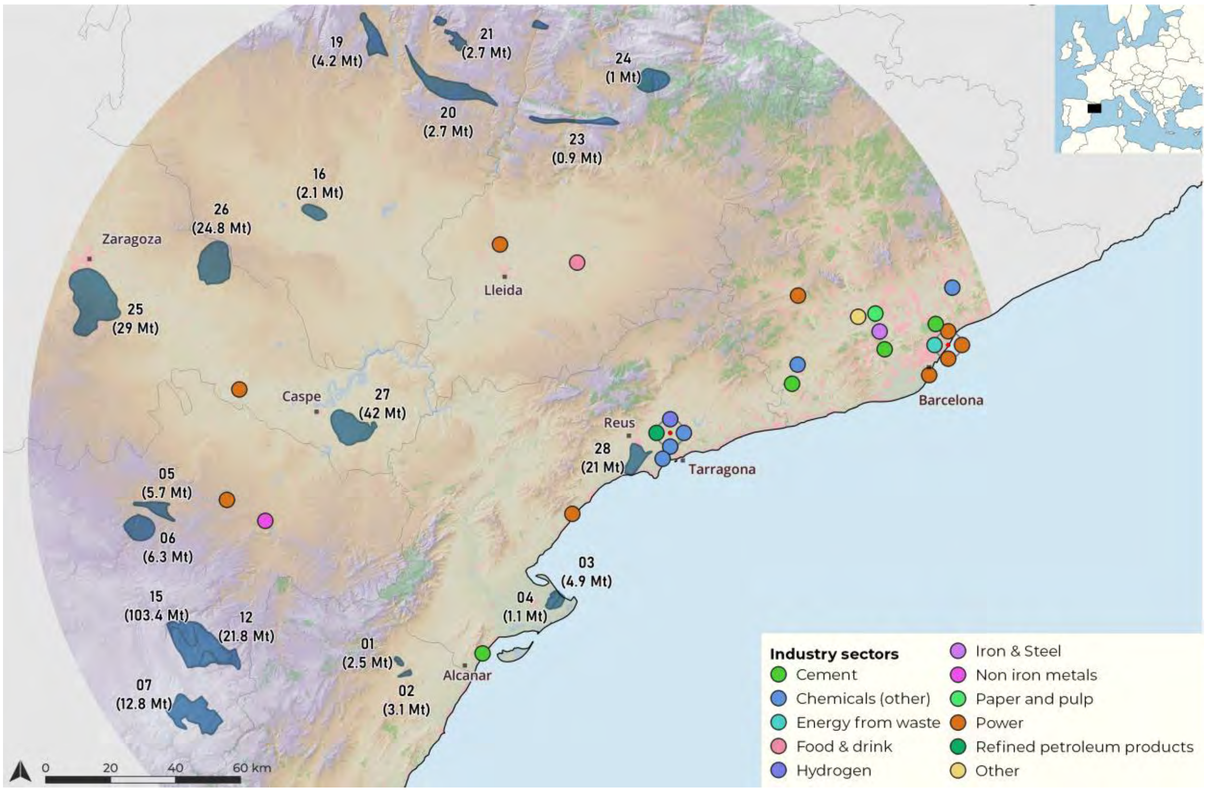

Figure 4-3 Storage units in the Ebro basin, represented as blue polygons. Numbers represent the *unit ID* in Table 4-2. Numbers In brackets stand for the storage capacity in Mt. For detail see map in Appendix I.

Furthermore, the 299 Mt total capacity is very unevenly distributed between the storage units. A single storage unit, the Maestrazgo-3 (SP.SU.15) in the Buntsandstein Facies (T1), provides 103 Mt capacity. Within the Maestrazgo structure there are two other storage units (Maestrazgo-1 SP.SU.7 and Maestrazgo-2 SP.SU.12) that add another 34.6 Mt of storage capacity. The second largest storage potential is provided by the Caspe Mayals storage unit (SP.SU.27), in the Cañizar Fm, Hoz de Gallo Fm (Buntsandstein Facies), with 42 Mt of estimated storage capacity (Table 4-2 and Figure 4-4). That is, the Maestrazgo and the Caspe Mayals storage units provide 60% of the storage capacity in the Ebro basin.

From the remaining 17 identified storage opportunities, there are three storage units with capacity between 20 Mt and 30 Mt, Lopin (SP.SU.25), Monegrillo (SP.SU.26) and Reus (SP.SU.28), with all others presenting a residual capacity, below 10 Mt. Given that the estimated storage capacity is expected to decrease with higher assessment tier, it is reasonable to assume that the Maestrazgo and Caspe Mayals storage units offer the best conditions for large scale implementation of geological storage of CO_2 for those sources near the Mediterranean coast, while the Monegrillo and Lopin structures seem to offer the best conditions for sources in the Zaragoza province (including those at Lleida) (Figure 4-4).

That does not mean that small storage units cannot be used, particularly if they are ideally located with respect to individual sources or groups of small-scale sources. For instance, the Reus storage unit (SP.SU.28) is near the group of sources at Pobla de Mafumet. The storage unit has an estimated storage capacity of 21 Mt, while the sources at Pobla de Mafumet emit currently 4.98 Mt/y. Large

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scale deployment of CCUS in the Reus industrial complex would need to resort to other locations for injection of CO_2 for periods longer than 4 to 5 years. However, there is an isolated source "Industrias Químicas Del Óxido de Etileno (la Canonja)" (SP.ES.22) at la Canonja, emitting 0.11 Mt/y, at around 7 km from the Reus unit. Although insufficient for Pobla de Mafumet, the Reus unit can provide storage for many years of the emissions from the La Canonja source.

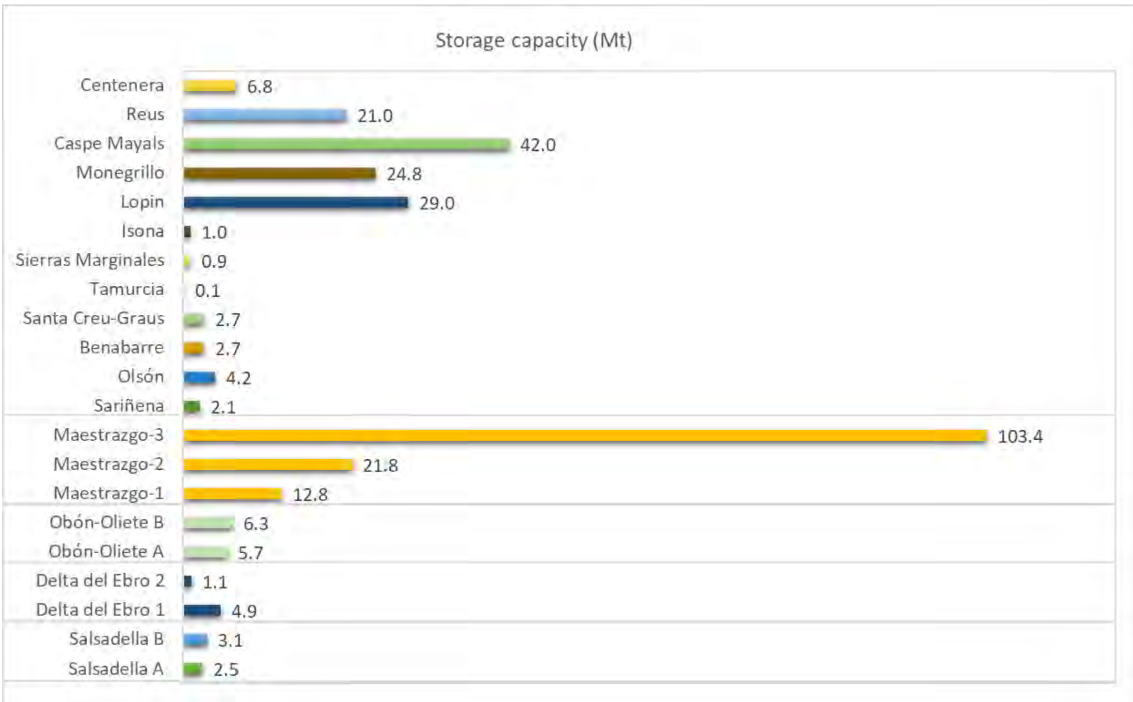
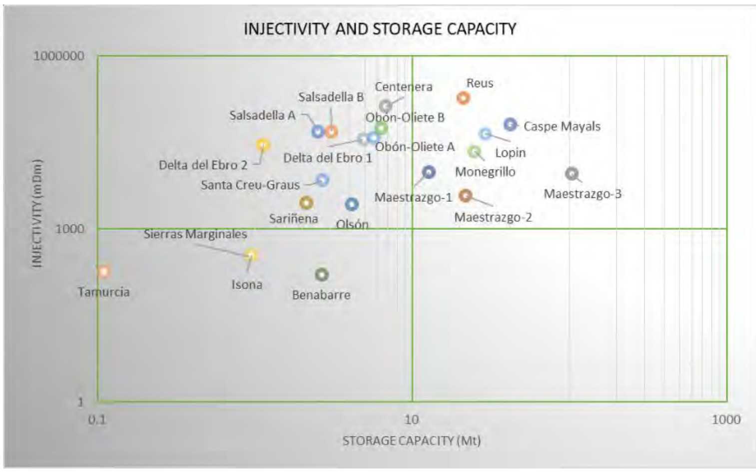


Figure 4-4 Distribution of storage capacity (Mt) per storage unit.

Nevertheless, those are isolated solutions and, in practical terms, considering the amounts of CO_2 currently emitted at the Reus and Barcelona sources, large-scale onshore storage of CO_2 would have to be directed mainly towards the Maestrazgo and Caspe Mayals storage units. That implies long transport distance, as these structures are at 230 km and 170 km in linear distance from Barcelona and 155 km and 95 km from Reus, respectively (Figure 4-3).



The same storage units are also preferential targets for the source "Industria de Transformaciones, S.A." in Calanda, and the power plant "Central de Escatron". Emissions from those sources are much smaller and they could be directed to sites with smaller storage capacity, but they are actually the two sites in the whole Ebro basin closer to the Maestrazgo and Caspe Mayals

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storage units.

The cement plant “Cemex España Operaciones (Alcanar)”, located close to Ebro’s delta, presents an interesting case, as it is located around 25 km linear from the Delta del Ebro-1 (SP.SU.3) and 2 (SP.SU.4) storage units, each with Tier 2 storage capacity below 5 Mt, insufficient for the current emissions of 0.78 Mt/y at the cement plant, and implying that CO_2 captured at this unit will probably be collected and transported together with the CO_2 from the sources around Reus.

Finally, the two sources at Lleida, currently emitting 0.41 Mt/y, may consider a storage opportunity in the Lopin and/or the Monegrillo Upper Cretaceous storage unit, at about 120 km and 90 km west from Lleida, and with a Tier 2 storage capacity of 29 Mt and 25 Mt, respectively. These storage units are farther away from Lleida than the Caspe Mayals storage unit, but topographic conditions for transport by pipeline may be more favourable to Lopin and Monegrillo. Furthermore, storage flexibility in the Ebro Basin would benefit if storage from the sources at Lleida is down in these storage units.

4.1.3 Spatial conditions for cluster and network development

Two seemingly natural clusters result from the spatial distribution of CO_2 emission sources in the Ebro basin: i) the Barcelona cluster and the ii) Reus cluster, with other sources being more dispersed or isolated to results in clusters (Figure 4-5). Both Reus and Barcelona are coastal areas, at more than 90 km from the relevant CO_2 storage sites (and for the Barcelona cluster, at more than 200 km from most storage sites).

The transport distance is significant and there are topographical and environmental constraints to consider. Terrain is relatively steep along most of the coastal region where many of the sources, and the two clusters, are located and even steeper terrain separates the main storage locations (Maestrazgo and Caspe Mayals) from the coastal area. Furthermore, some of the most mountainous areas also are natural parks. These are constraints that are best overcome by laying CO_2 transport routes along the corridors defined by the existing natural gas pipelines, which already follow the valleys and plains in the area.

Not surprisingly, the railway network follows roughly along the same corridors, and several sources do have dedicated rail terminals, but the option of transport by railway can be feasible only for small, isolated emitters. There are also port facilities in Barcelona and Tarragona (7 km from Reus), and although storage is onshore, scenarios can consider transport by ship between the two ports, i.e. between the Barcelona and the Ebro clusters.

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Table 4-2 Main features of potential storage units in the Ebro basin

Storage Unit ID	Storage type	Storage_Unit	Daughter unit	Formation	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)	Injectivity (mDm)
SP.SU.1	DSA	Salsadella	Salsadella A	Buntsandstein Facies (T1)	Sandstone	Onshore	1475	164	2.52	49200
SP.SU.2	DSA	Salsadella	Salsadella B	Buntsandstein Facies (T1)	Sandstone	Onshore	2555	164	3.05	49200
SP.SU.3	DSA	Delta del Ebro	Delta del Ebro 1	Buntsandstein Facies (T1)	Sandstone	Onshore	1202	120	4.88	36000
SP.SU.4	DSA	Delta del Ebro	Delta del Ebro 2	Lower Cretaceous, Miocene	Carbonate & breccia	Onshore	488	97	1.13	29100
SP.SU.5	DSA	Obón-Oliete	Obón-Oliete A	Buntsandstein and Muschelkalk1 Facies	Sandstone & Dolomite	Onshore	525	130	5.69	39000
SP.SU.6	DSA	Obón-Oliete	Obón-Oliete B	Buntsandstein and Muschelkalk1 Facies	Sandstone & Dolomite	Onshore	665	190	6.32	57000
SP.SU.7	DSA	Maestrazgo	Maestrazgo-1	Imón Fm. (T3)	Carbonate	Onshore	1413	137	12.76	9590
SP.SU.12	DSA	Maestrazgo	Maestrazgo-2	Muschelkalk Facies (M3)	Carbonate	Onshore	1494	54	21.82	3780
SP.SU.15	DSA	Maestrazgo	Maestrazgo-3	Buntsandstein Facies (T1)	Sandstone	Onshore	2285	130	103.43	9100
SP.SU.16	DSA	Sariñena	Sariñena	Imón Fm. (T3)	Carbonate	Onshore	1946	41	2.12	2870
SP.SU.19	DSA	Olsón	Olsón	Arenisca de Arén Fm (Eocene sup)	Sandstone	Onshore	1215	38	4.15	2660
SP.SU.20	DSA	Benabarre	Benabarre	Isábena Fm (Lias)	Carbonate	Onshore	850	16	2.67	160
SP.SU.21	DSA	Santa Creu-Graus	Santa Creu-Graus	Calizas de Centenera (Senonense-K2)	Carbonate	Onshore	1990	100	2.68	7000
SP.SU.22	DSA	Tamurcia	Tamurcia	Lower-Middle Jurassic	Carbonate	Onshore	2450	18	0.11	180
SP.SU.23	DSA	Sierras Marginales	Sierras Marginales	Lower Jurassic (Liass)	Carbonate	Onshore	2400	33	0.92	330
SP.SU.24	DSA	Isona	Isona	Lower Jurassic (Liass)	Carbonate	Onshore	1754	35	0.95	350
SP.SU.25	DSA	Lopin	Lopin	Buntsandstein Facies (T1)	Sandstone	Onshore	992	150	29.01	45000
SP.SU.26	DSA	Monegrillo	Monegrillo	Buntsandstein Facies (T1)	Sandstone	Onshore	1075	74	24.84	22200
SP.SU.27	DSA	Caspe Mayals	Caspe Mayals	Cañizar Fm, Hoz de Gallo Fm (Buntsandstein Facies)	Sandstone	Onshore	659	218	41.99	65400
SP.SU.28	DSA	Reus	Reus	Malm (Upper Jurassic)	Carbonate	Onshore	1380	144	21.03	187200
SP.SU.29	DSA	Centenera	Centenera	Upper Cretaceous	Carbonate	Onshore	2140	450	6.8	135000

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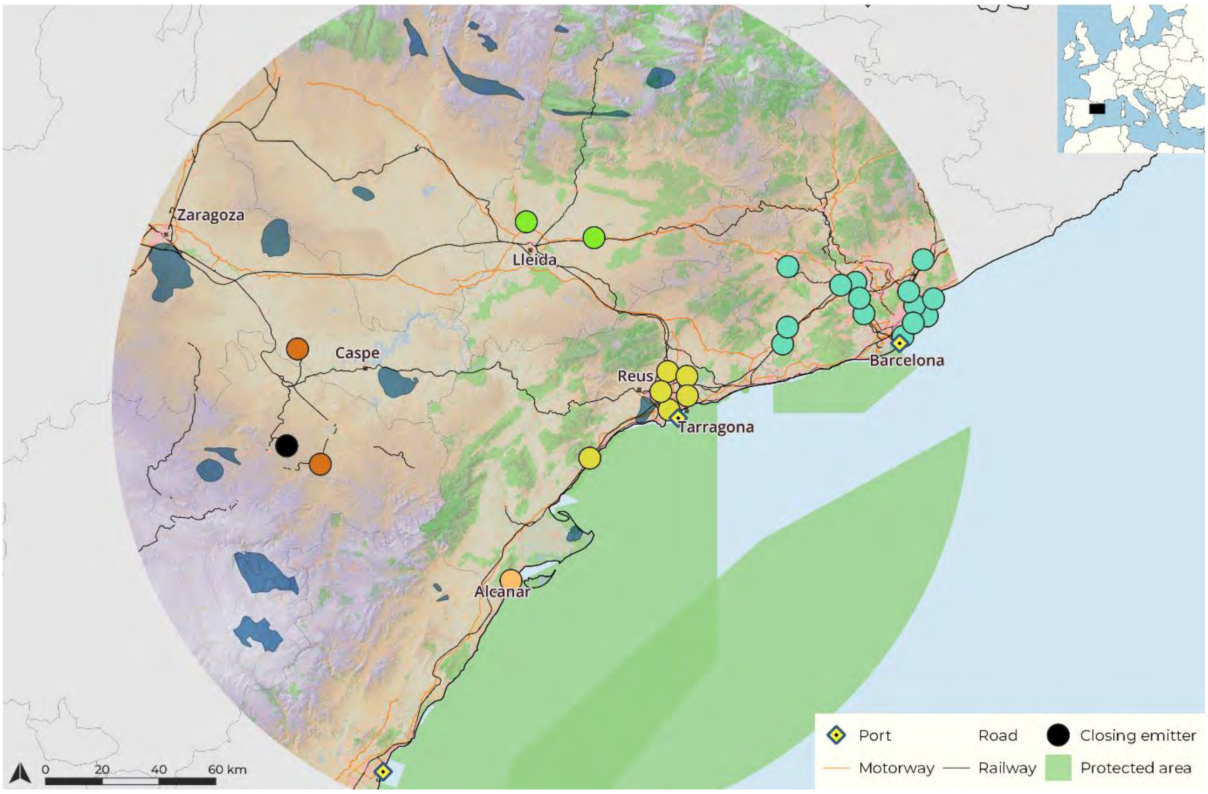

Figure 4-5 Clustering of CO_2 emitters and location of possible transport modes (railways and ports). Light blue - Barcelona cluster, yellow - Reus cluster, green - Lleida sources, Orange - sources at Andorra. Blue polygons are the storage sites.

Given that the most promising storage locations (Maestrazgo and Caspe Mayals) are located to the west and southwest of Barcelona and Reus sources, it is reasonable to envisage a transport configuration that, starting from Barcelona leads SW to Reus, finds a joint collection hub with the Reus sources, and then is trunk transported to Caspe Mayals and/or Maestrazgo along the corridor of the existing natural gas pipeline that crosses the hills of Muntanyes de Prades.

In general, the CO_2 sources are in rural or industrial complexes, so that no major issues are anticipated for finding space to build capture facilities or CO_2 consolidation hubs, but some sources in the Barcelona cluster are within a more challenging urban environment.

In the Barcelona cluster fourteen of the facilities are in or around the Barcelona city limits, amounting to 5.7 Mt/y of maximum capture potential (admitting the Endesa power plant at Andorra will effectively close in 2020). This group of sources includes two cement plants with emissions above 1 Mt/y, with a third cement plant emitting 0.43 Mt/y. The power sector is also relevant, with three fossil fuel power plants and one urban waste plant emitting 2.49 Mt/y.

Given the highly urbanised character of the area, there can be spatial difficulties for building new large-scale capture facilities. Each of the point sources is well connected to roads and railways, with all sources, except for "Stahl Ibérica" (SP.ES.16), being connected to operational railway branches (Figure 4-6). However, the options of transport by road or rail could only be valid for very small sources (such as "Uficsa" (SP.ES.20), "Cales de Pachs, S.A." (SP.ES.25), and "Seat" (SP.ES.24) sources, all

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around 0.1 Mt/y), but even in those cases the urban and suburban environment can turn that possibility unfeasible.

There are no pipeline corridors specifically reserved in the clusters (and in the promising region), but all potential sources in Barcelona have a connection to or are near an existing natural gas pipeline. Most likely these pipelines will continue running natural gas for decades, but there could be some advantage in utilising the same corridor to build CO_2 pipelines. These can be even more important for those sources located within the urban area of Barcelona, where space availability and safety measures are more challenging. The collection network could follow the same path as the natural gas pipelines that are set along valleys or green corridors in Barcelona.

The cement sources are the most relevant and are best positioned to act as a collection hub, since they are emplaced in industrial complexes already outside city limits.

The Reus cluster (near Tarragona) includes six sources currently producing 4.98 Mt/y, centred around the Repsol Refinery and including one hydrogen production plant (Hyco, SP.ES.11), three chemical plants and a power plant "Central de Ciclo Combinado Plana Del Vent" (SP.ES.14). The most important emitters are the "Dow Chemical Iberica (Dow Nord)" and the Repsol Refinery.

The sources in the Reus cluster are located within the same industrial perimeter, at La Pobla de Mafumet, distancing not more than 2.5 km from each other, sharing all the same transport possibilities and apparently without spatial constraints for building new capture facilities or collection hubs (Figure 4-8).

The "Industrias Químicas del Óxido de Etileno (La Canonja)" (SP.ES.22), a minor emitter in this group (0.1 Mt/y), is located in a different industrial area in Tarragona, around 8 km from the Reus industrial perimeter, while the power plant "Central de Ciclo Combinado Plana Del Vent" (SP.ES.14), is more than 35 km SE from the Reus industrial perimeter. Still, even these two sources are located along a railway, roadway and natural gas pipeline that connects them to the Reus industrial perimeter (Figure 4-7). The emissions from the power plant are too high and will require collection by pipeline, but the emissions from the La Canonja chemical plant are small and may be suitable for transport by rail or for injection separately from the other sources at the Reus storage unit, which has enough capacity for such a small source.

From Reus two branches of the natural gas pipeline cross along valleys the mountains to the west and continue to the Caspe Mayals and Maestrazgo regions. These features seem to make the Reus group of sources an ideal configuration for an ICCUS cluster.

The other six sources in the Ebro basin are less ideally located to form clusters by themselves, as they are more scattered and considerably distant from Reus and Barcelona. The cement factory "Cemex España Operaciones (Alcanar)" currently responsible for emissions 0.78 Mt/y, is distant from any other major sources (Figure 4-7). It is in a rural area and space constraints should not be a major problem. Transporting CO_2 directly by pipeline to the onshore storage sites is likely to be unfeasible, as topography is quite steep to the west and there are some natural parks that would have to be crossed. Thus, either this source is able to store CO_2 in a geological sink nearby (such as the Delta del Ebro-1 and 2, but capacity is small) or transport is likely to be made to the NE, to join the collection

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hub at Reus. Transport to Reus could follow the existing pipeline corridor or could be made by ship, since the cement plant is served by the Port industrial d'Alcanar, 85 km from the Tarragona port.

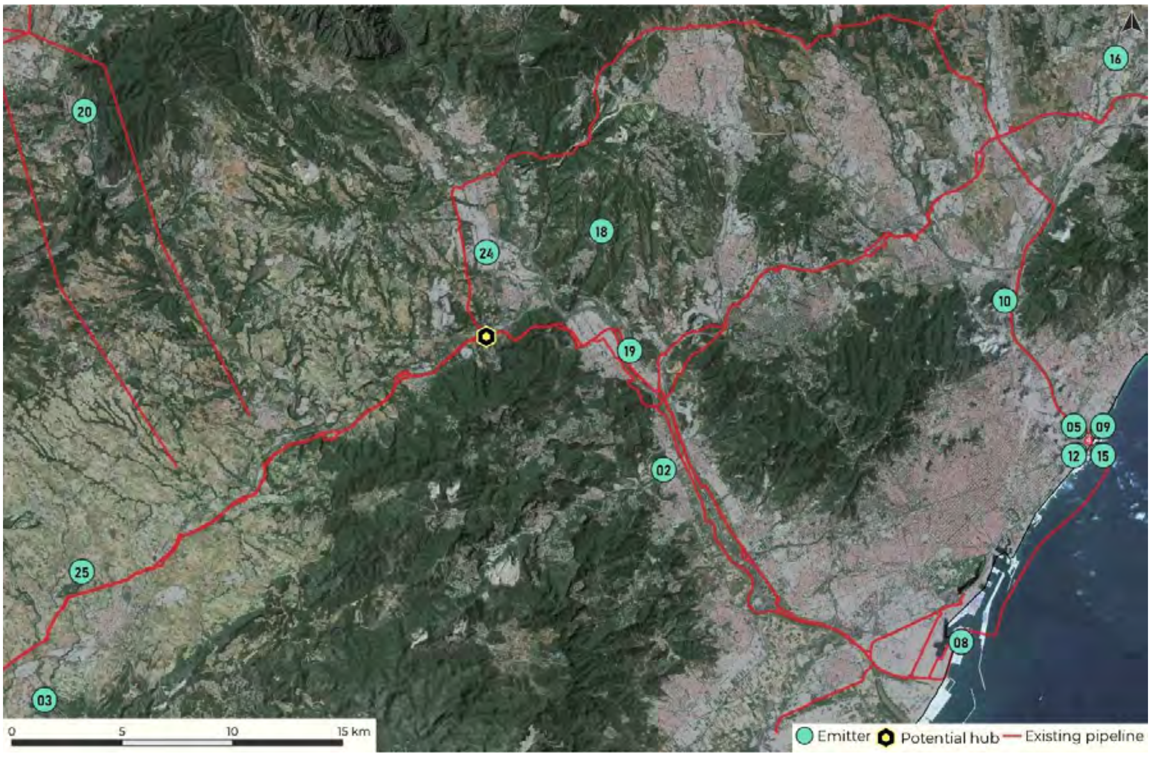
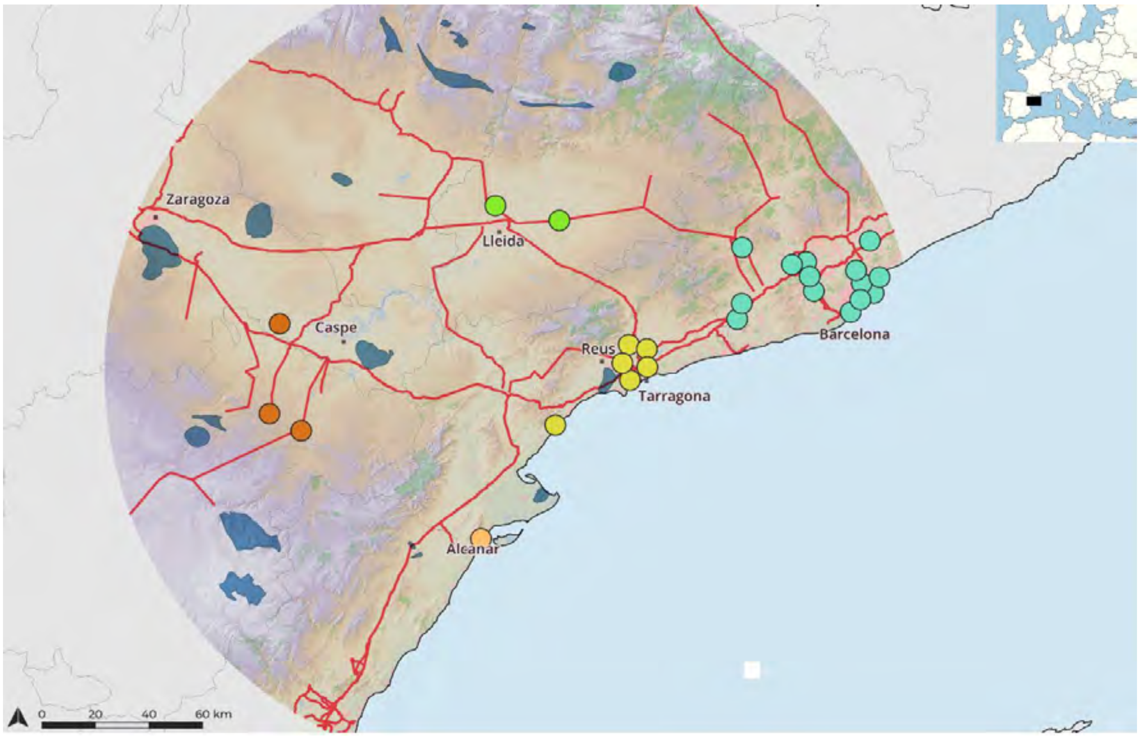


Figure 4-6 Sources around Barcelona, also showing the existing natural gas pipeline network following



along valleys and going offshore along the Port area.

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Figure 4-7 Clustering of CO_2 sources and location existing natural gas pipelines.

In the outskirts of the city of Lleida are the cogeneration plant "Alier (planta de cogeneracio)" (SP.ES.21) and the food & drink factory "S.A.T. Nufri 1956" (SP.ES.17), together responsible for emissions of 0.32 Mt/y, of which 0.062 Mt/y are derived from biomass and biogas combustion. These are relatively small-scale sources, both located in rural areas. Unlike the sources in Reus and Barcelona, topography and environment protected areas are less challenging here.

The power plant is located 24 km west from the food & drink facility, and given the small volume of CO_2 produced, storage sites located to the west, Lopin (SP.SU.25) and Monegrillo (SP.SU.26), can provide enough capacity (Figure 4-7). Volumes emitted by the power plant probably will require transport by pipeline, which could also collect CO_2 from the food & drink facility (although the volumes emitted by this facility may be compatible with transport by rail for instance), at common hub near the power plant.

Finally, the non-iron metal transforming unit "Industria de Transformaciones, S.A." (SP.ES.23) emitting a little more than 0.1 Mt/y, located in Calanda, Teruel, and the power plant "Central de Escatron" (SP.ES.13) in Escatron, Zaragoza, emitting 0.34 Mt/y, are around 40 km from each other, but much more distant from any other sources (Figure 4-7). They are, however, the two facilities closest to a larger number of storage units (Obón-Oliete A (SP.SU.5) and B (SP.SU.6), Caspe Mayals, Maestrazgo and Monegrillo) and it is possible they do not need to integrate a cluster or network for CCUS to be implemented. Both are served by natural gas pipelines and railway terminals. In fact, given the low level of emissions, the Obón-Oliete A and B storage units, distancing around 30 km from the sources and with a total storage capacity of 12 Mt, can be considered as a storage opportunity for these two sources, provided Tier 3 and Tier 4 assessments do not result in a strong decrease in the estimated storage capacity.

As said, Endesa power plant at Andorra is due to shut down in 2020, but scenarios to be developed for CCUS development in the Ebro region, should consider the possibility that the facilities may be reutilised for other purposes.

The development of a CO_2 transport network in the Ebro basin is well served by multiple transport possibilities, and although the storage sites are all onshore, there is also the possibility that ship transport can be used between some of clusters located along the Mediterranean coast. In fact, the sources grouped around Barcelona are served by the Barcelona port (some power plants are actually located at the port side), which could be used to transport CO_2 by ship to the Tarragona port that serves Reus, or vice-versa, before being transported along a trunk pipeline to the storage sites. The two ports are 90 km distant.

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Figure 4-8 Sources in the Reus cluster. The combined cycle power plant is located further to the SW and is not shown in the image.

4.1.4 CO_2 utilisation options

National plans and recent laws related to climate, energy transition or both do not mention CO_2 utilization or CO_2 valorization in particular although these technologies can be included indirectly through other lines such as circular energy (and CO_2 re-used), waste recycling (and CO_2 mineralization), bio-fuels laws (CO_2 capture by biomass) or GEI industry reduction incentives and plans. At local level, the Government of Cataluña has been the first in Spain developing a “Law for Climate Change” in 2017 where indirect actions, similar to those at national level, are included.

It must be mentioned that from industry, academy and administration the need of development of a regular framework for CO_2 utilization is known and requested to the national government.

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The road map for CO_2 utilization in Spain is shown in the next figure from 2018 where CO_2 utilization is highly depended on capture technology in place and a development of technologies for the use of CO_2 is not expected in the short term.

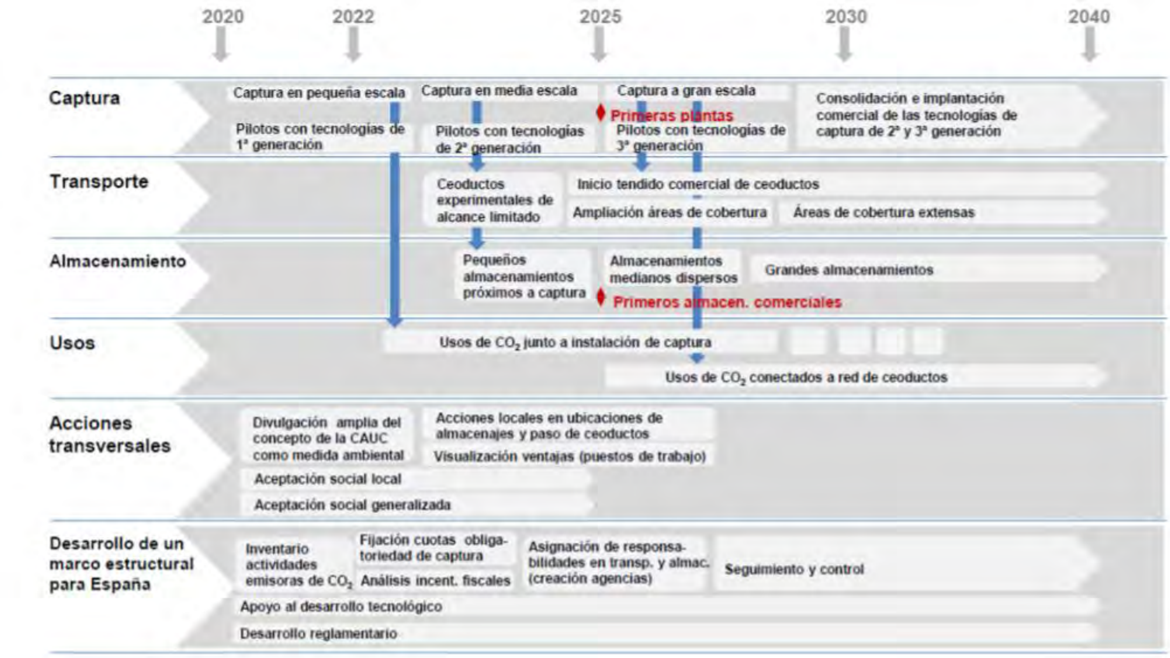

Figure 4-9 Roadmap of CCUS technologies in Spain by ALLINE (2018)

4.1.4.1 *On-going CCU projects and research lines*

Many research centres and industries are working on the development of CO_2 utilization technologies. Special interest has the work developed by "Instituto Catalán de Investigación Química", ICIQ, (Catalan chemical research Centre), located in Tarragona, appointed by the Catalan Government as the main actor for climate change innovation and being CO_2 uses a key line of research (PTECO2 & SUSCHEM, 2019):

- **A-leaf** (TRL 2-4): An Artificial Leaf, a photo-electro-catalytic cell from earth-abundant materials for sustainable solar production of CO_2-based chemicals and fuels. European project with Instututo Catalán de Investigaciones Químicas, IMDEA (Madrid) and Universitat Jaume I (Valencia) as Spanish partners.

- **BIORECO2VER** (TRL 3-5) : BioRECO_2VER aims to demonstrate the technical feasibility of more energy efficient and sustainable non-photosynthetic biotechnological processes for the capture and conversion of CO2 from industrial point sources like refineries and cement production plants into valuable platform chemicals, i.e. isobutene and lactate. European project with IDENER as Spanish partner.

- **eCOCO2** (TRL 5): eCOCO2 combines smart molecular catalysis and process intensification to bring out a novel efficient, flexible and scalable CCU technology. The project aims to set up a CO_2 conversion process using renewable electricity and water steam to directly produce synthetic jet fuels with balanced hydrocarbon distribution (paraffin, olefins and aromatics)

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to meet the stringent specifications in aviation. European project with University of Valencia and CSIC as Spanish partners.

- **Co2Fokus** (TRL3): CO_2 utilization focuses on market relevant dimethyl ether production, via 3D printed reactor - and solid oxide cell-based technologies. European project with TECNALIA as Spanish partner.

- **FReSMe** (TRL 6): this project aims to demonstrate the whole process that enables the CO_2 captured from the steel industry to produce methanol fuel that will be used as fuel in the ship transportation sector. The Methanol fuel produced will be applied in an end-user demonstration. Funded by H2020 EU program, with *i-deals* as Spanish partners.

- **ArtifUEL**(TRL 1-3): Artificial Photosynthesis for the production of solar fuels and chemicals' and '"Nanostructured Semiconductor-Metal Complex based Hybrid Photocatalyst for Solar Water Splitting and CO_2 Reduction' for which researchers from the Heriot-Watt University of Edinburgh, UK and the Council of Scientific & Industrial Research, CSIR, of India, respectively has joined the Photoactivated Processes Unit. IMDEA is the Spanish partner.

And other research lines are being carried out currently in Tarragona area, Cataluña and Spain:

- Transforming CO_2 into Cycling Carbonates using linocellulosic waste as catalysis (TRL 1). Universitat of Rovira I Virgili (Tarragona).

- Nanocatalysts for Sustainable Synthetic Fuel Production (TRL 3-6), Institut de Recerca en Energia de Catalunya (IREC).

- Development and study of a bioelectrochemical reactor for the conversion of CO_2 to CH4 (TRL 5-6). LEITAT Technological Center, Terrassa, Spain.

- Electroquimical CO_2 valorization for formic acid production (TRL 3-4) – Grupo Depo from University of Cantabria.

- Fixation of CO_2 by bacteries for bioplastics. (TRL 3-4). CIB-CSIC (Madrid)

4.1.4.2 Carbon use perspective in Ebro Basin

Although the CO_2 utilization technologies are mainly in research phase, there are 4 research lines (mineralization, fertilizers, methanol production and polymers) where some work is being done and forecasts of development for the current years (2021 to 2030) has been presented by ALINNE (2018):

Table 4-3 – CO_2 uses perspectives in Spain

CO_2 use technology	Annual mean (Mt/Y) (2015-2020)	Expected annual mean (Mt/y) (2021-2030)
Mineralization	1.12	0.8
Fertilizers	0.89	1.04
Methanol production	0.14	1.85
Polymers production	0.14	0.26

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These figures are proposed for Spain, but it must be considered that 25% of total chemical industry of Spain are in the Tarragona area.

Chemistry and fuels

25% production from chemical industries in Spain are from Tarragona, including Dow Chemical (ethylene and derivate products, polymers), Carburos Metálicos (Air Products Group) producing and providing gases (CO_2 included) to industry and medicine, and Tarragona Industrial Complex of REPSOL (polymers, fuels). As an example, REPSOL has produced for the first time in Spain biofuel for aviation few months ago in Puertollano Refinery.

Based on reviewed research projects, the process carries out for the CO_2 conversion could be:

- Methanol, methane, formic acid … by electroreduction.
- Biofuels: in-situ electrolysis and water removal from hydrocarbon synthesis reaction. This intensified process can lead to breakthrough product yield and efficiency for chemical energy storage from electricity, specifically CO_2 per-pass conversion > 85%, energy efficiency > 85% and net specific demand < 6 MWh/t CO_2. In addition, the process is compact, modular –quickly scalable- and flexible, thus, process operation and economics can be adjusted to renewable energy fluctuations (Project eCOCO$_2$) or by **artificial photosynthesis** (projects e-leaf, Artifuel, FotoFuel and others).

These companies have defined or are defining a future strategy where CO_2 utilization is included. It is not expected to be put in place at short term, but it could be in the mid to long term.

Building materials/carbonation

Many cement industries are also located in the Ebro Basin area and it is considered the valorization of waste material (e.g. slags, ashes, kiln dust, tailings, etc.), or from the construction/demolition sector to create diverse products with CO_2 injected as part of the recycling process. This material could be mixed with raw material and be used in road foundations or in the preparation of fresh concrete, construction bricks and blocks, concrete fillers, etc.

Based on reviewed research projects, the process carries out for the mineralization process could be by acceleration of natural process where Ca (calcium)- or Mg (magnesium) react with carbon dioxide (CO_2) to produce calcium or magnesium carbonate (CaCO3 or MgCO3).

It is not expected its application at short or medium term.

Algae

Algae act as biological CO_2 filters, capturing CO_2 by photosynthesis and producing biomass used for human food or biofuels.

It is not expected its application at short or medium term.

Other

CO_2 as heat transmission fluid is proposed by the cement industry with high potential for CO_2 utilization in its own industry if oxy-combustion system is in place. The installation of one of this plant is planned at experimental phase but it is considered to have high potential.

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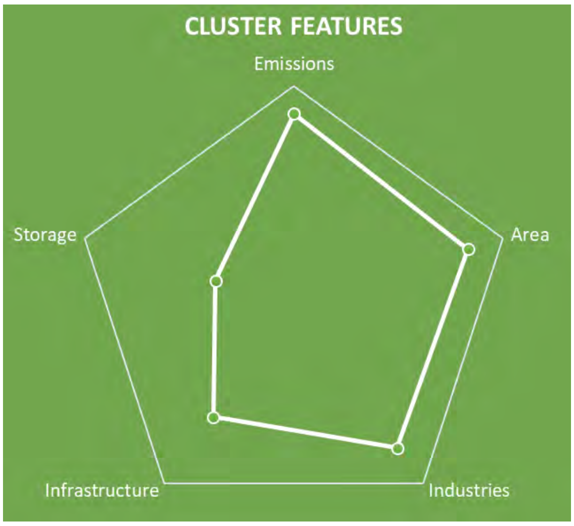
4.1.5 Main features of technical potential for ICCUS development

The high level of emissions in the Ebro basin from the industrial sector and their concentration in two main industrial areas, Reus and Barcelona, are the strongest motivators for engaging in ICCUS implementation. Several of the sources are actually placed in the same industrial perimeter at Reus and at the Barcelona port. This could provide ideal conditions for cooperation to develop a common network (Table 4-4).

The cement sector in the Barcelona cluster and the petrochemical industry, in the Reus cluster are probably the aggregators of other industries to join ICCUS clusters. Some sources are in the Barcelona urban area, but most are in rural or industrial complexes and should not have spatial difficulties to build capture facilities.

There are topographical challenges to build pipeline networks, but the existing natural gas pipelines defines corridors that can be of value. Furthermore, most sources are connected to operational railway lines and some to ports. Industrial complexes in Reus and Barcelona can be used as sites for consolidation hubs before trunk transport by pipeline for onshore storage.



Storage capacities are exclusively onshore, sometimes very distant from the main sources (in some cases more than 200 km) and are only acceptable in capacity, requiring some management and flexibility on injection in the main storage sites. Offshore storage opportunities should be sought.

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Table 4-4 Ebro Basin cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	Two main loci: Barcelona and Reus. In Barcelona, cement plants (3), power plants (2) and a waste power plant. In Reus, a refinery and chemical sources (3) and a power plant. Six other relevant sources spread in the study area	+
	Emission volume distribution	Several large point sources specially cement plants in Barcelona, and the refinery in Reus. Also, sites with multiple vents.	+
	Emission volume profile	One coal power plant closing, cement sector with a downward trend, but most sources with a stable trend and some growing.	+
	Emissions type and quality	Mostly combustion emissions, except for the cement sector and some in the chemical sector. No high concentration sources.	~
AREA	Industrial area character	Chemical industries, iron & steel and power plants in Barcelona mostly adjacent to urban areas. Some located at ports. All other sources in rural areas or in industrial polygons.	~
	Importance of industry	Reus and Barcelona are major industrial areas.	+
	Cluster recognition	Area had previously been included in clusters in COMET project, centred in the Barcelona, Reus and Lleida sources, with storage at Maestrazgo	+
INDUSTRIES	Integration of industry	Refinery and chemical industry in Reus integrated in the same industrial polygon at Pobla de Mafumet. Power plants and power from waste plant in Barcelona also integrated in the same industrial port area.	+
	Decarbonisation alternatives	Potential for hydrogen fuel use at refineries, biomass in use (consider BECCS?) Cement sector with less alternatives for decarbonisation.	~
	CCU	Potential for CO_2 usage for producing synthetic fuels. Given the relevance of cement sector, uses of CO_2 in building materials should be considered.	+
	Motivation for decarbonisation	National strategies for climate mitigation	~
	Motivation for CCS	Repsol is an important emitter but can also be a player in business models for storage	+
INFRASTRUCTURE	CO_2 collection options	Sources are connected to natural gas pipelines which could be used as the corridor for CO_2 pipelines. Rail links to most major emitters, with operational terminals. Ports could be an alternative for transportation between Barcelona and Reus sources.	+
	CO_2 consolidation options	Sources in and around Barcelona could face difficulties for consolidation due to highly urbanised area. All other sources with plenty of space available for CO_2 consolidation, in particular around Reus.	+
	Existing CO_2 infrastructure	No existing infrastructure, but following closure of Andorra power plant some natural gas pipeline branches will no longer be used. Experience in managing underground gas storage offshore.	+
	Infrastructure reuse options	Existing pipelines likely to continuing running natural gas, unlikely to be available for reuse. Following closure of Andorra power plant some natural gas pipeline branches will no longer be used.	-
STORAGE	Storage accessibility	Best storage sites onshore are more than 200 km distant from sources in the Barcelona and more than 100 km from the Reus sources.	-
	Storage capacity	Acceptable for the best sites, totalling 180 Mt, with another 110 Mt provided by many small-scale structures.	~
	Storage flexibility	Acceptable, since only a small number (5) of structures present storage capacity above 20 Mt.	~
	Storage development integration	No organisation has put forward plans for developing storage, but Repsol one of the main emitters in the area, has the capability to develop storage.	~

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4.2 Galati region – Romania

4.2.1 Emissions and industry sectors

STRATEGY CCUS inventoried eight large scale CO_2 emitter in Romanian Galati region (Figure 4-13), although three units are either shutting down or in standby status. Thus, only five units are active in Galati; three power plants, one iron & steel mill and one non-iron metals plant. Still, in the scenarios to be developed in STRATEGY CCUS the possibility that some of the closed or standby units being revived should not be discarded.

Total emissions in this promising region amounted to 4.56 Mt/y, in 2019, but a single facility, "Liberty Galati SA" iron & steel mill (RO.ES.7) was responsible for 4.19 Mt/y, that is 92% of the total. All other sources are much smaller, with the "Alum S.A. - Sectia CET, Instalatia Calcinarea AL(OH)$_3$" non-iron metals plant (RO.ES.5) at Tulcea, being the second largest emitter, with 0.26 Mt/y in 2019. The three power plants are very small emitters, in the range 0.01 to 0.05 Mt/y (Figure 4-10).

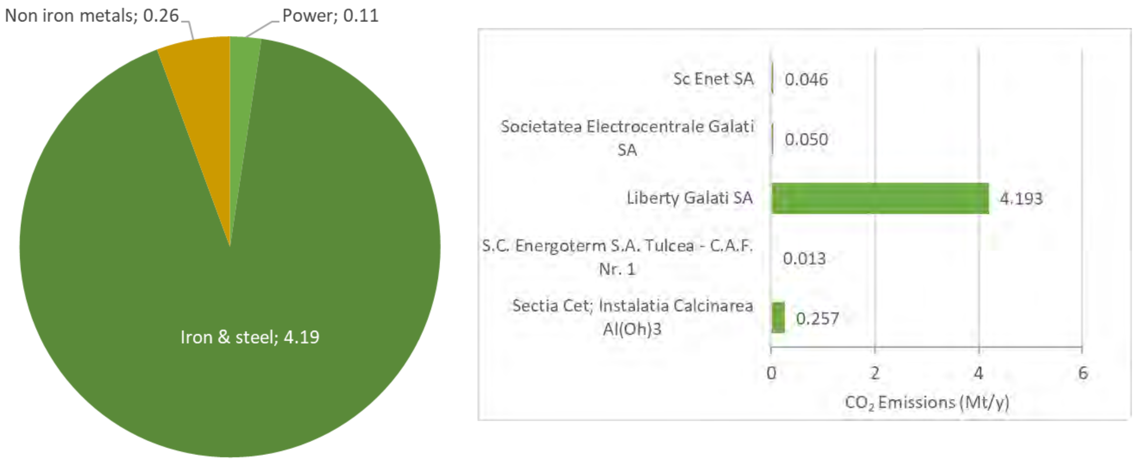

Figure 4-10 Emissions (in Mt/y) per sector and per facility in the Galati region.

The sources are spread along a NW-SE axis, in the cities of Focsani (SC Enet power plant), Tulcea (non-iron metals plant and a power plant) and Galati (the iron & steel mill and Galati power plant) which is the main emission centre.

Besides the shutdown of three facilities, the total emissions in the Galati sources have been decreasing in recent years, with all active five facilities showing a "falling" trend (Table 4-5).

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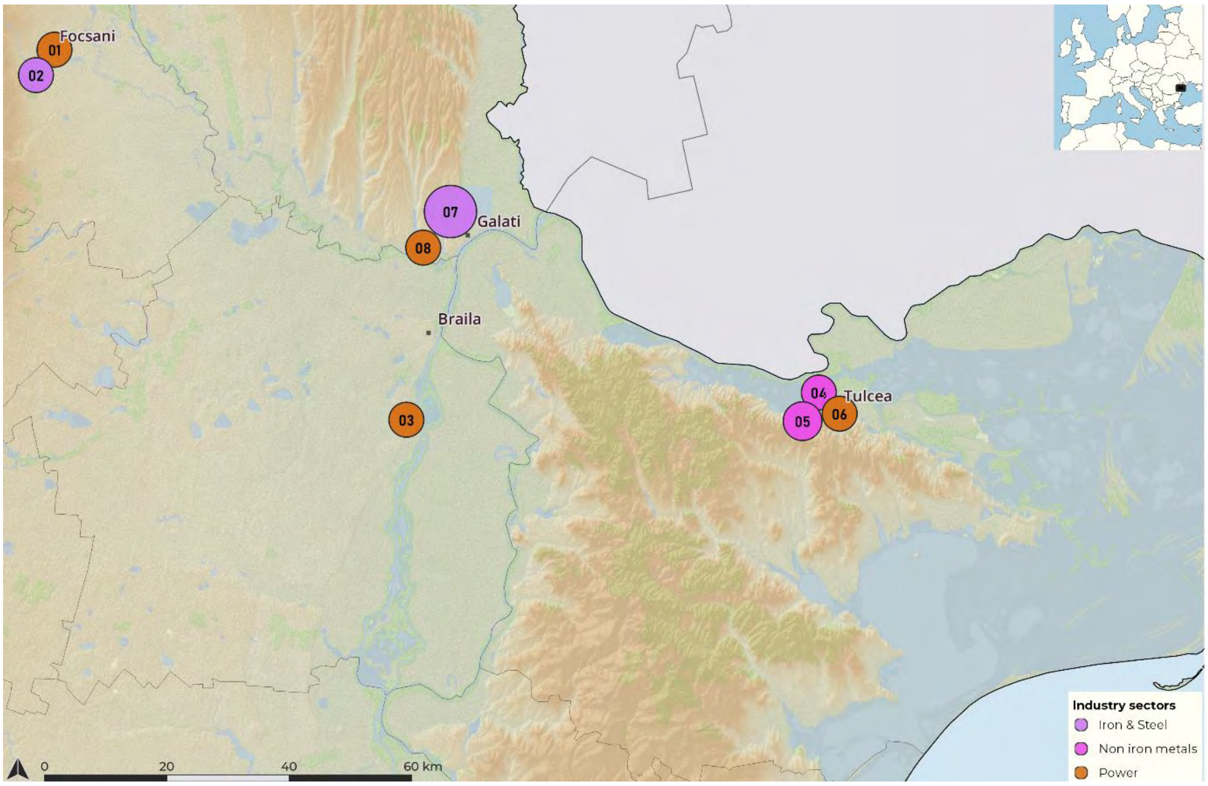

Figure 4-11 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-5Table 4-1. For detail see map in Appendix I.

Table 4-5 Main features of CO_2 emitting facilities in the Galati region

Emitter ID	Facility name	Sector	Location	Emissions (tCO_2/y)	Emission trend
RO.ES.1	Sc Enet SA	Power	Focsani	46230	Falling
RO.ES.2	Sc Power Steel Company SRL	Iron & Steel	Focsani	-	Closing
RO.ES.3	S Complexul Energetic Oltenia SA - Se Chiscani	Power	Braila	-	Closing
RO.ES.4	Sc Tremag SA	Non iron metals	Tulcea	-	Closing
RO.ES.5	Alum S.A. - Sectia Cet; Instalatia Calcinarea Al(Oh)3	Non iron metals	Tulcea	257313	Falling
RO.ES.6	S.C. Energoterm S.A. Tulcea - C.A.F. Nr. 1	Power	Tulcea	12998	Falling
RO.ES.7	Liberty Galati SA	Iron & Steel	Galati	4193464	Falling
RO.ES.8	Societatea Electrocentrale Galati	Power	Galati	49662	Falling

4.2.2 CO_2 Storage possibilities

The CO_2 storage possibilities in the Galati Region include:

a) onshore storage at the Focsani Trough, southern Carpathian Basin and North Dobrogea Promontory;
b) offshore storage at the Histria Depression, Black Sea Basin.

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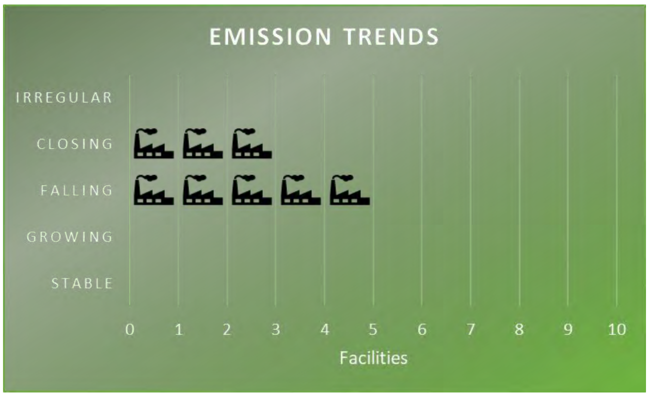
Deep Saline aquifers could not be delimited onshore as very little data is available, but a few potential aquifers have been screened offshore (Figure 4-13Figure 4-13 Potential storage units in the Galati region. Numbers represent the *unit ID* in Table 4-6. For detail see map in Appendix I.).



Onshore, within Focsani Trough geological basin, eleven hydrocarbon fields have been identified with CO_2 storage potential (Table 4-6): six oil fields (Filiu, Jugureanu-Odăieni, Oprișenești, Bordei Verde Est, Plopu and Lișcoteanca), and five producing gas fields (Balta Albă, Ghergheasa, Roșioru, Bobocu and Boldu).

Within North Dobrogea Promontory, four storage options have been identified: two oil fields (Tepu and Grivita Nord) and two gas fields (Matca and Cudalbi). The hydrocarbon fields are located on the same structural alignment. The productive formation is the Sarmatian, at depths of 1494 - 2269 m. The traps are structural.

Only three hydrocarbon fields are already abandoned and can be considered for CO_2 injection exclusively for climate mitigation purposes (Figure 4-12). Those are the "Bobocu" (RO.SU.2), "Grivita Nord" (RO.SU.7) and the "Filiu" (RO.SU.14) depleted hydrocarbon fields. There are no storage capacity estimations for these abandoned fields, but the "Bobocu" field has an area of 7.18 km^2 and is much larger than the other two fields. "Bobocu" DHF is located 85 km west from Galati city in a rural setting, with very low population density. Assessing the capacity estimate in the "Bobocu" field is a priority has it could be a solution for CO_2 storage in the Galati Region.

Other onshore DHFs still under exploration also seem to have an interesting potential once they become depleted. Namely, the "Rosioru" (RO.SU.5) field, still producing, and located in the same region as the "Bobocu", is a large hydrocarbon field for which a large storage capacity is expected.

Offshore, the Histria Depression, located in the western part of the Black Sea Basin, presents good possibilities for CO_2 storage and utilization (CO_2-EOR). Four oil fields (Sinoe, Lebada West, Lebada East and Pescarus) have been identified, all of which are still producing.

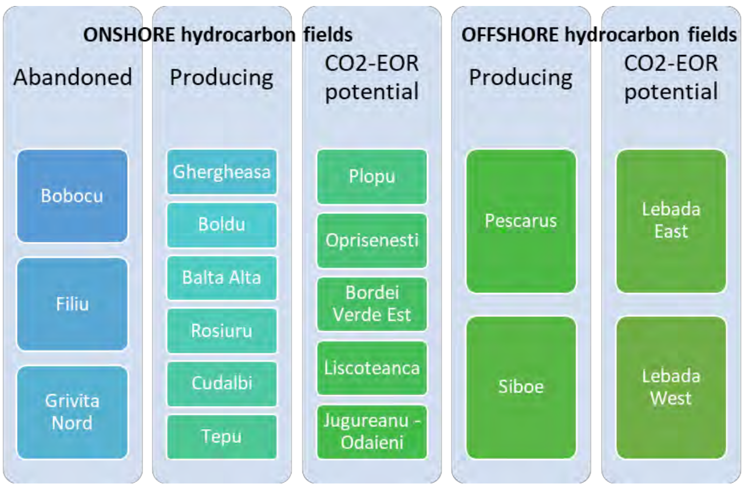


Figure 4-12 Situation of the hydrocarbon fields in the Galati region.

The onshore and offshore fields still producing oil can also be considered for CO_2 injection if combined with EOR. In particular five onshore fields ("Matca" (RO.SU.8), "Plopu" (RO.SU.10),

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"Oprisenesti" (RO.SU.11), "Bordei Verde Est" (RO.SU.12) and "Liscoteanca" (RO.SU.13)) two offshore DFHs ("Lebada East" (RO.SU.19) and Lebada West" (RO.SU.20) have been identified as targets for CO_2-EOR.

Apart from the oil fields, three deep saline aquifer structures have been identified offshore: "Iris" (RO.SU.23), "Lotus" (RO.SU.18) and "Tomis" (RO.SU.23). The only potential CO_2 geological storage reservoir that can be correlated on the three structures is the Albian reservoir represented by grey sandstones with limestone cement on the depth interval 2700 - 2844 m in Tomis, quartz sandstones with limestone cement developed on the interval 1821 - 1835 m in Lotus and quartz sandstones with limestone cement on the interval 2600 – 2615 m in Iris.

Regarding storage capacity, there are prior estimates made in the EUGeoCapacity and CO_2 StoP projects for two onshore oil fields: "Tepu" with 5 Mt and "Ghergheasa" with 50 Mt capacity. Offshore, storage capacity estimates have been made in a national research project for the deep saline aquifers, "Iris", "Lotus" and "Tomis", with a combined storage capacity of 17 Mt (Table 4-6).

Obviously, the onshore depleted hydrocarbon fields present ideal conditions for storage of CO_2, since the geological structure are well known and containment conditions are proven, but the utilisation of CO_2 for EOR purposes, onshore or offshore, may provide economic incentives to deploy carbon dioxide capture.

As for the deep saline aquifers, it is difficult to envisage that they can be useful for CO_2 storage, due to the offshore setting, low capacity and much lower level of knowledge about the geological conditions than for the hydrocarbon fields.

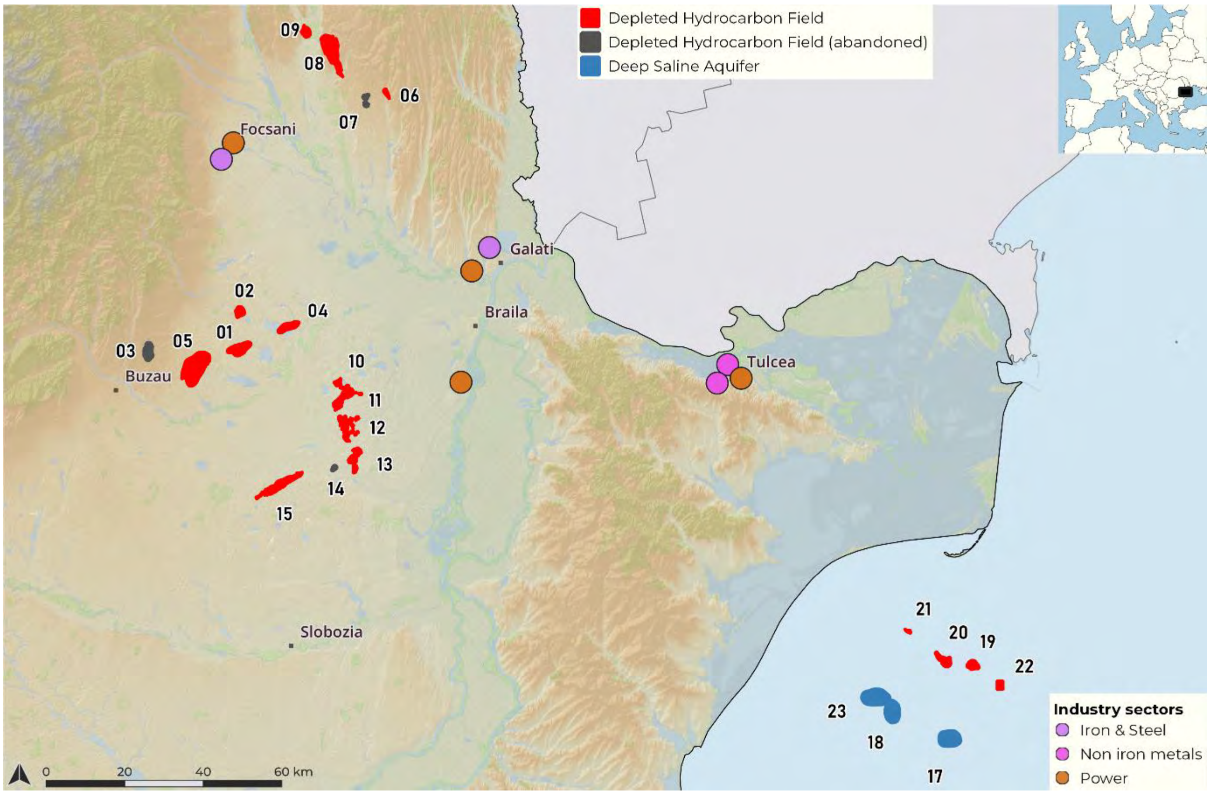

Figure 4-13 Potential storage units in the Galati region. Numbers represent the *unit ID* in Table 4-6. For detail see map in Appendix I.

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Table 4-6 Main features of potential storage units in the Galati region

Storage Unit	Storage type	Storage_Unit	Formation	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)	Status
RO.SU.1	DHF	Ghergheasa	Pontian	sands	Onshore	1892	100	50	Producing
RO.SU.2	DHF	Boldu	Pontian	sands	Onshore	1500	50		Producing
RO.SU.3	DHF	Bobocu	Pontian	sands	Onshore	2500	100		Abandoned
RO.SU.4	DHF	Balta Alba	Pontian	sands	Onshore	1500	100		Producing
RO.SU.5	DHF	Rosioru	Pontian	sands	Onshore	2000	100		Producing
RO.SU.6	DHF	Cudalbi	Sarmatian	sands	Onshore	1850	100		Producing
RO.SU.7	DHF	Grivita Nord	Sarmatian	sands	Onshore	2000	100		Abandoned
RO.SU.8	DHF	Matca	Sarmatian	sands	Onshore	2000	100		Producing
RO.SU.9	DHF	Tepu	Sarmatian	sands	Onshore	1800	100	5	Producing
RO.SU.10	DHF	Plopu	Meotian	sands	Onshore	1300	38		Producing
RO.SU.11	DHF	Oprisenesti	Meotian	sands, calcareous sandstones, sandstones	Onshore	1370	38		Producing
RO.SU.12	DHF	Bordei Verde Est	Meotian	sands	Onshore	1250	38		Producing
RO.SU.13	DHF	Liscoteanca	Meotian	sands	Onshore	900	38		Producing
RO.SU.14	DHF	Filiu	Sarmatian	sandy limestones	Onshore	1300	60		Abandoned
RO.SU.15	DHF	Jugureanu - Odaieni	Sarmatian	sandy limestones	Onshore	1300	60		Producing
RO.SU.16	DSA	Venus	Eocene	detrital facies at bottom, on top carbonates	Offshore	1000	300		
RO.SU.17	DSA	Tomis	Albian	grey sandstones with limestone cement	Offshore	2700	100	5.3	
RO.SU.18	DSA	Lotus	Albian	quartz sandstones with limestone cement	Offshore	1821	30	4.8	
RO.SU.19	DHF	Lebada East	Albian	clastic rocks with intercalations of carbonates	Offshore	2000	50		Producing
RO.SU.20	DHF	Lebada West	Albian	clastic rocks with intercalations of carbonates	Offshore	2000	50		Producing
RO.SU.21	DHF	Sinoe	Albian	clastic rocks with intercalations of carbonates	Offshore	2000	50		Producing
RO.SU.22	DHF	Pescarus	Albian	clastic rocks with intercalations of carbonates	Offshore	2000	50		Producing
RO.SU.23	DSA	Iris	Albian	quartz sandstones with limestone cement	Offshore	2600	100	6.6	

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4.2.3 Spatial conditions for cluster and network development

The five operational sources in the Galati promising region are located around the cities of Galati, Tulcea and Focsani (Figure 4-14).

The only large-scale source, the “Liberty Steel Galati SA” steel mill (RO.ES.7) is in Galati, within an industrial complex where constraints to build new facilities are probably not an issue. The industrial complex is outside the city limits, and any connection to a CO_2 transport infrastructure does not require crossing urban areas. Within the same industrial complex is the power plant “Societatea Electrocentrale Galați S.A.” (RO.ES.8), which emitted 0.049 Mt in 2019, an amount nearly insignificant compared to 4.2 Mt/y from the steel mill (Figure 4-15).

Capturing CO_2 at the Galati steel-mill equates to capturing 92% of the regional emissions. The Galati industrial complex as a dedicated rail terminal that runs to the west, passing near the depleted hydrocarbon reservoirs of “Bobocu” and the producing field of “Ghergheasa”, where storage capacity is assessed at 50 Mt. The industrial complex is less than 3 km away from the Danube river, a possible transport point to the east, into the Black Sea and the offshore CO_2-EOR opportunities, such as the “Lebada East” and “Lebada East” oil fields.

However, the volume of emissions at the Galati stell mill is very high and not adequate to transport by road, rail or river. The industrial complex is connected to the existing natural gas pipeline network that runs, in one branch, towards the gas fields in the west, and in another branch towards the offshore hydrocarbon fields. Given that the gas fields are still operating, reutilising the pipelines is probably not feasible, but the same corridor could be used for a pipeline to be built and transport CO_2. Onshore storage could be either at the “Bobocu” depleted hydrocarbon field, or on the several CO_2-EOR possibilities. Offshore storage would probably be justified if CO_2-EOR is implemented at the “Lebada” oil fields.

Sixty km downstream from Galati, along the Danube, at Tulcea there are two active sources, the non-iron metals plant “Alum S.A. -Sectia CET. Instalatia calcinarea Al(OH)3” (RO.ES.5) with emissions of 0.26 Mt/y and the power plant “S.C. Energoterm S.A. Tulcea” (RO.ES.6) with nearly negligible emissions of 0.013 Mt/y.

“Alum S.A. - Sectia CET, Instalatia Calcinarea $AL(OH)_3$” (RO.ES.1) is in an industrial complex, again without apparent issues about space for building capture facilities or the need for CO_2 transport to cross urban areas. As in Galati, this industrial complex is nearby a river that runs to the Black Sea, and also has a dedicated rail terminal, although the railway does not lead to the areas with storage potential. The existing natural gas pipeline network does connect to Tulcea. The amount of CO_2 available for capture is possibly small enough to consider transport in liquid phase by waterway, downstream to the offshore sites, or upstream to a consolidation hub with the Galati sources.

Finally, at Focsani, the “Sc Enet SA” power plant emits only 0.046 Mt/y. A second source, the “SC POWER STEEL COMPANY SRL” steel mill (RO.ES.2) has closed recently. Emissions from the “SC Enet SA” power plant are probably too small to be worth considering for CO_2 capture (representing 1% of the emissions in Galati). However, if CO_2 capture is implemented, given the small amounts, the transport could be made in liquid phase to the relatively nearby “Bobocu” DHF (RO.SU.3) which is

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accessible by rail and road. Alternatively, the Danube could again be used for transport to a consolidation hub at Galati.

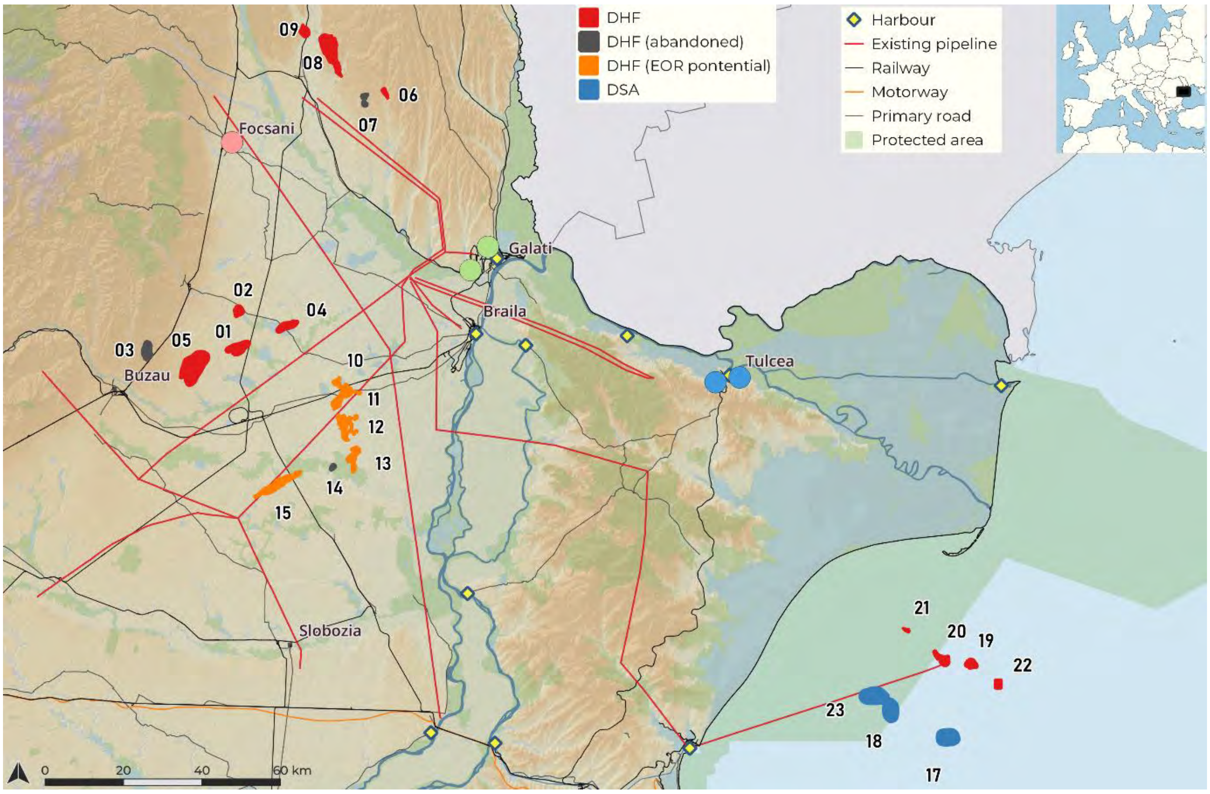

Figure 4-14 Clustering of CO_2 emitters and possible transport modes (roads, railways and ports). Red lines depict the existing pipelines. Note the location of the oil fields with potential for CO_2-EOR and the possible corridor formed by the existing pipeline networks.

4.2.4 CO_2 utilisation options

Utilisation of CO_2 as the working fluid in Enhanced Oil Recovery is the most likely CO_2 utilisation to be implemented in the Galati region. The industrial profile of the region, leaves little room for other opportunities, since there are no major refineries or chemical sectors that can utilise CO_2 in conversion processes, nor is there a cement sector that can use CO_2 to produce cured cements or aggregates for construction. However, such facilities exist in other parts of Romania and transport to those facilities should be considered in the scenarios to be developed in WP5.

Within the Galati region itself, clearly CO_2-EOR is the readiest to apply CO_2 utilisation, particularly in the onshore oil fields “Matca”, “Plopu”, “Oprisenesti”, “Bordei Verde Est” and “Liscoteanca” and in the two offshore fields “Lebada East” and Lebada West”.

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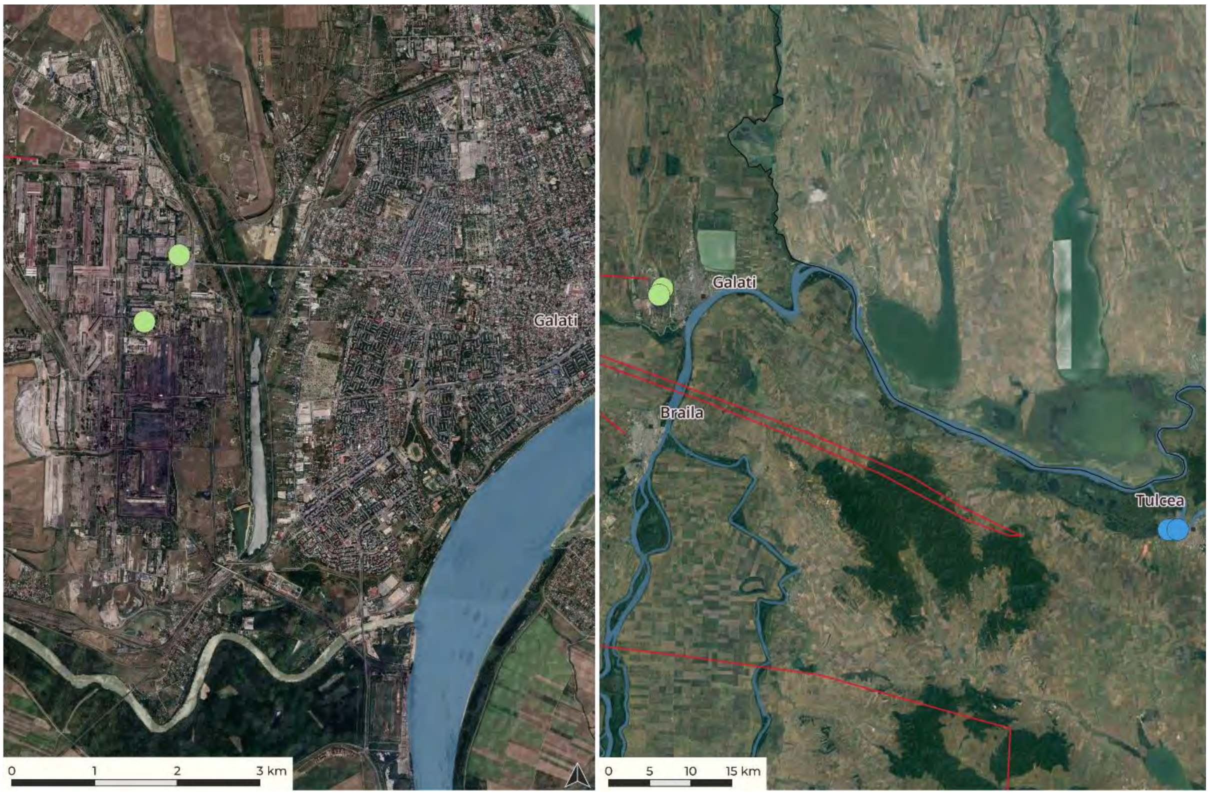
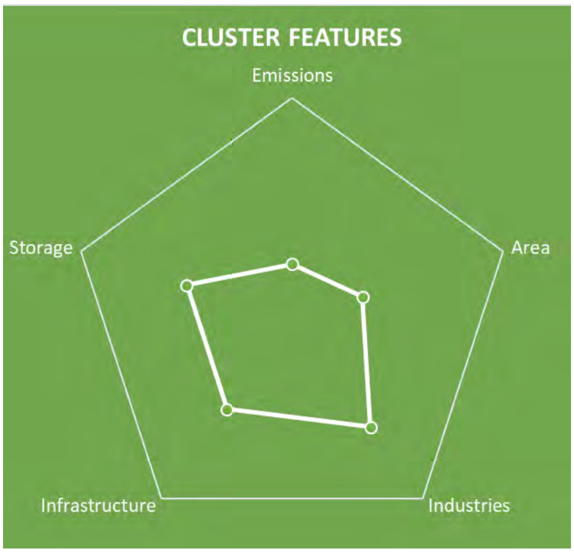


Figure 4-15 Left: Sources in the industrial complex of Galati. Red line is the natural gas pipeline connecting to the industrial complex and bottom right shows the Danube. Right: locations of Tulcea and Galati along the Danube river.

4.2.5 Main features of technical potential for ICCUS development

"Liberty Steel Galati" steel mill at Galati is the single large-scale emitter in Galati, and the source for which implementing CCUS could be relevant and, possibly, become and aggregator for smaller sources at Focsani and Tulcea. The decreasing importance of the industry in the region leaves little motivation for building CO_2 storage infrastructures but may also facilitate the planning for implementation of the technology at the Galati industrial complex, as less involvement of multiple industrial facilities would be required.



CO_2-EOR could provide the motivation for engaging in CO_2 capture and transport, since several oil fields, onshore and offshore have potential for applying it.

If decoupled from CO_2-EOR, the depleted hydrocarbon reservoirs onshore would be the best option for storage, has the geological conditions are well known and are in low density population areas, decreasing risks. However, currently there is no storage capacity assessment

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conducted for those DHF.

The industrial areas in Galati, Tulcea and Focsani are well connected to the onshore hydrocarbon fields by the existing natural gas networks and perhaps the same corridors could be used.

Offshore storage is probably only an option to consider if linked to utilisation of CO_2 for EOR purposes at the "Lebada" oil fields.

Table 4-7 Galati cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	Small number of active sources (5) in three cities, Galati, Tulcea and Focsani.	~
	Emission volume distribution	One single source, "Liberty Steel Galati", is responsible for 92% of the emissions in the region.	-
	Emission volume profile	All sources show a decreasing trend in emissions	-
	Emissions type and quality	Mostly combustion emissions in power plants, steel mills and non-iron plant. No high concentration sources.	~
AREA	Industrial area character	Industry is located in industry complexes outside urban limits.	+
	Importance of industry	Low. Closing of industrial facilities is further reducing it.	-
	Cluster recognition	Not previously considered as a cluster	-
INDUSTRIES	Integration of industry	At Galati the steel mill and a power plant are integrated in the same industrial complex. Other sources do not seem integrated.	~
	Decarbonisation alternatives	Energy efficiency is indicated as the main alternative for reducing emissions.	+
	CCU	EOR in the hydrocarbon fields, onshore and offshore is probably the best possibility.	~
	Motivation for decarbonisation	National strategies for climate mitigation	~
	Motivation for CCS	The steel is a heavy emitter and could face competitive and public acceptance issues if it does not decrease emissions.	~
INFRASTRUCTURE	CO_2 collection options	The steel mill is connected to a natural gas pipeline and is close to the Danube river. Other sources also close to river.	+
	CO_2 consolidation options	Sources are in industrial area, there should not exist problems of space for consolidation hubs.	+
	Existing CO_2 infrastructure	No existing infrastructure.	–
	Infrastructure reuse options	Existing pipelines likely to continuing running natural gas, since hydrocarbon fields are still producing.	-
STORAGE	Storage accessibility	Distance to onshore DHF is on the order of 80 km. Onshore sites are about 30 km from the shoreline and about 150 km from the largest source.	+
	Storage capacity	Large gaps in storage capacity assessment. Insufficient capacity in DSA, all of which are offshore. Estimates for two DHF of 55 MT, but several others hydrocarbon fields without capacity assessment.	-
	Storage flexibility	Currently flexibility is low, since only 3 DHF are abandoned, but as producing DHF become depleted, flexibility should increase.	~
	Storage development integration	No organisation has put forward plans for developing storage, but ArcellorMittal is a multinational company with previous involvement and interest in the technology-	~

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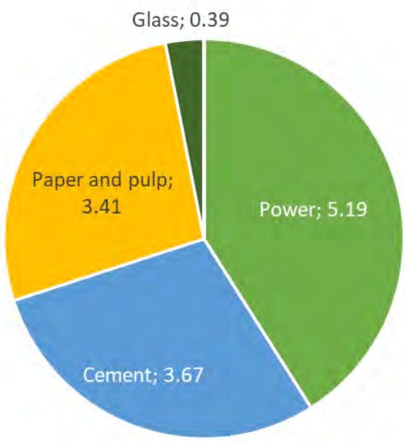
4.3 Lusitanian basin – Portugal

4.3.1 Emissions and industry sectors

The CO_2 emitters inventory in the Lusitanian basin identified sixty-eight sources with total CO_2 emissions of 13.08 Mt/y in 2018. Twenty sources have been retained as potential targets for CO_2 capture, with emissions ranging from 0.08 Mt/y to 2.79 Mt/y (Table 4-8). The joint emissions from those twenty sources are 12.66 Mt/y, that is 97% of total in the region.

From the ensemble of thirteen industrial sectors considered in STRATEGY CCUS cluster building methodology, only sources from four sectors were retained in this promising region (Figure 4-16):

- Five power plants, which released 5.19 Mt of CO_2 to the atmosphere in 2018;
- Five cement plants and one lime producing facility, emitting 3.67 Mt/y;
- Five paper & pulp plants, with total emissions of 3.41 Mt/y, the vast majority of emissions being from the combustion of biomass and, thus, not accountable for the national GHG budget;
- Four glass factories, much lower carbon emitters than the other sectors, with total emissions in 2018 of 0.39 Mt CO_2.



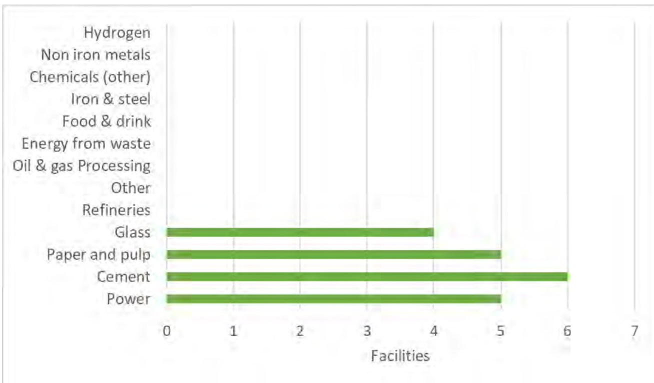


Figure 4-16 Emissions (in Mt/y) and facilities per sector in the Lusitanian basin. Emissions from the Paper & Pulp sector according to the E-PRTR database 2017, while for the other sectors EU ETS 2018 is the reference.

There are no high CO_2 concentration sources inventoried in the region (with emissions above the threshold 0.08 Mt/y), the highest concentration being at a maximum of 20% in some of the cement plants.

The current main source, the "Pego" coal power plant (PT.ES.1), is planned to shut down in 2021, decreasing considerably the total emissions in the region. Nonetheless, the facility owners are studying the conversion of the power plant to run on biomass. At the same industrial complex, there is a CCGT Power Plant "Central de Ciclo Combinado do Pego" (PT.ES.6) that started operations in 2011 and will continue running for several years. If the biomass becomes the main fuel at the Pego Power plant, opening the possibility for negative emissions through BECCS, the industrial complex at Pego could become a possible locus for CO_2 capture in the Lusitanian basin.

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Still, and given the relevance of process emissions, it is in the cement sector (Table 4-8), with higher CO_2 concentration, that the best possibilities for deploying the full chain of CCUS technologies, including geological storage, are found. CCUS technologies are expected to be a complement to all the decarbonisation priority actions occurring in the sector and the cement plants equipped with this technology could become steady CO_2 suppliers to convert into value-added products as part of the National Strategy for Hydrogen (EN-H2).

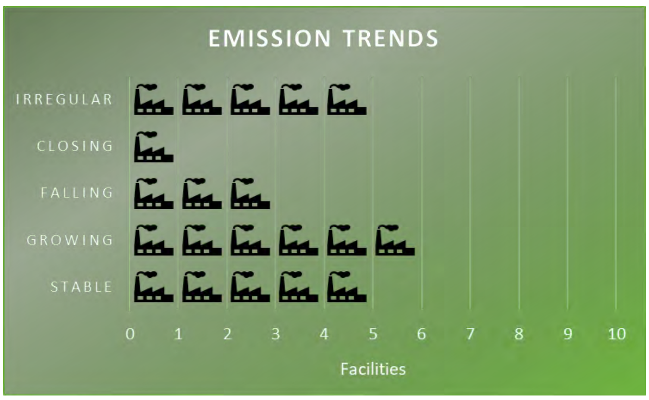
The cement plants are scattered throughout the region and, by themselves, do not define potential clusters. The industrial axis between Lisbon and Setúbal includes two large scale plants, "Centro de Produção de Alhandra" (PT.ES.2) and "Fábrica SECIL – Outão" (PT.ES.5), emitting 0.94 Mt/y and 0.84 Mt/y, while at the northern part of the region, the plant "Centro de Produção de Souselas" (PT.ES.3), with emissions of 0.89 Mt/y, is somewhat isolated, at more than 35 km from the nearest sources.

Smaller scale cement plants (PT.ES.9 and PT.ES.11) exist near Marinha Grande, at the centre of the promising region. Although with lower emissions, they are closer to sources in the glass sector and to the Lime production facility (PT.ES.8), which can result in synergies between these sectors to implement CCUS.

Today, in Portugal, waste biomass fractions represent around 20% of the total fuel mix used in some of the cement plants, and this might even increase, in the future, to 30 or more than 40%, opening also the possibility for negative emissions through BECCS.

In the same Lisbon-Setúbal axis there is also a natural gas power plant "Central Termoelétrica do Ribatejo" (PT.ES.4) and a co-generation plant "Central de Cogeração do Barreiro" (PT.ES.15), as well as the "About the Future" Paper & Pulp mill (PT.ES.10) which emitted in 2017 more than 1.31 Mt, with 1 Mt/y being from the combustion of biomass.

In fact, the Paper & Pulp sector is responsible for large-scale emissions, especially at the "About the Future" (PT.ES.10) and the Celbi (PT.ES.19) facilities, each emitting more than 1 Mt/y. The three other facilities in the same sector (PT.ES.12, PT.ES.13 and PT.ES.20) emit in the range 0.23 Mt/y to 0.44 Mt/y. In all cases the major source of emissions is biomass combustion, and therefore the sources tend to carbon neutrality. Nevertheless, the need for a steadily supply of CO_2 in the scope of the National Strategy for Hydrogen (see section 4.3.4) makes the sector an interesting target for CO_2 capture, specially if combined with BECCS, providing the opportunity to achieve negative emissions. This possibility is reinforced by the clustering of "Soporcel" (PT.ES.12), "Soporcel Plus" (PT.ES.13) and "Celbi" (PT.ES.19) mills, which are in the same industrial area, near Figueira da Foz.



The glass sector is traditionally important in the target region. Although emitting considerably less that the cement or the power plants, they are clustered around the areas of Marinha Grande and Figueira da Foz. The four glass factories emit 0.39 Mt/y, but they are already spatially clustered and, despite the low level of emissions, could become the focus to form ICCUS clusters

together with the nearby cement plants (near Marinha Grande) and Paper & Pulp mills (at Figueira da Foz).

Natural gas is the main fuel utilised in the power plants (given that the coal power plant will shut down), glass sector, and in the quicklime plant "Indústria Mineral - Prod Cales não Hidráulicas" (PT.ES.8). The cement plants at Alhandra (PT.ES.2) and Souselas (PT.ES.3) run primarily on petcoke, but also utilise biomass. Not surprisingly, fossil fuel combustion is the main source of emissions, with process emissions being relevant only in the cement sector, where up to 65% of the emissions are not related to fuel combustion. In this sector, natural gas could also be used as a fuel but its price has not proven to be competitive until now, despite plants' proximity to the natural gas grid.

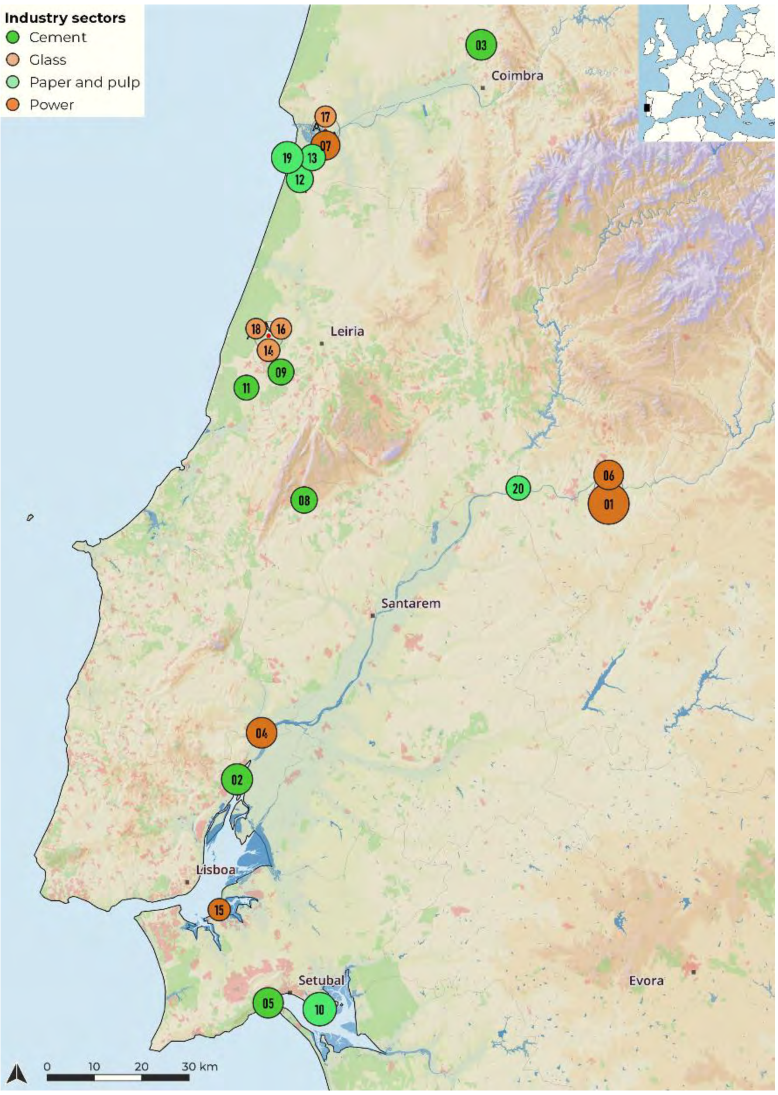


Figure 4-17 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-8.For detail see map in Appendix I.

Emissions from biomass originate mostly in the five Paper & Pulp mills, where 2.7 Mt/y of CO_2 is emitted each year from biomass combustion.

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Apart from the shutdown of the Pego coal power plant, there is not a clear decreasing trend in emissions in the area, as six of the sources are showing a growing trend in emissions, while only two of the major sources (the “Alhandra” and “Souselas” cement plants) depict a decreasing trend. Natural gas power plants exhibit in general an irregular pattern, mainly related to the need to meet power demand in dry years with less available renewables. In the short term with the close of the coal power plants, natural gas units will have an important role in electricity system stability, which may lead to an increase of its activity and CO_2 emissions.

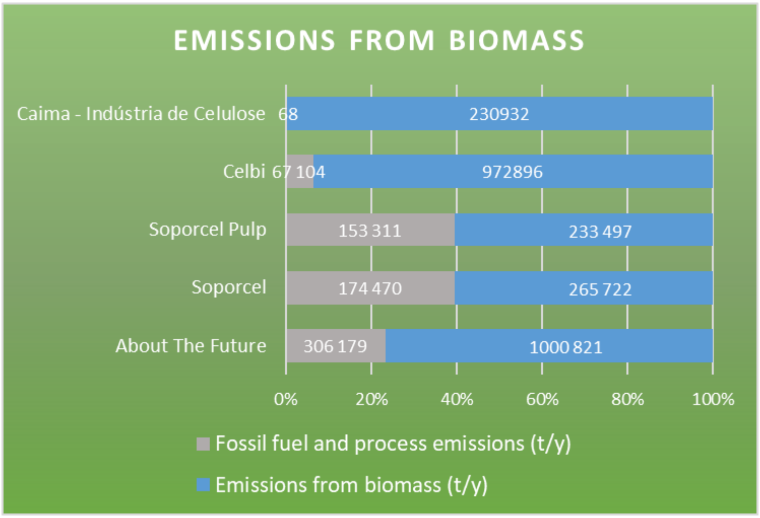

Table 4-8 Main features of CO_2 emitting facilities in the Lusitanian basin

Emitter ID	Facility name	Sector	City	Emissions (tCO_2/y)	Emission trend	Main fuel
PT.ES.1	Central Termoeléctrica do Pego	Power	Pego	2792 244	Irregular	Coal
PT.ES.2	Centro de Produção de Alhandra	Cement	Alhandra	940 174	Falling	Petcoke
PT.ES.3	Centro de Produção de Souselas	Cement	Souselas	889 585	Stable	Petcoke
PT.ES.4	Central Termoelétrica do Ribatejo	Power	Carregado	869 142	Growing	Natural Gas
PT.ES.5	Fábrica SECIL - Outão	Cement	Outão	835 267	Falling	
PT.ES.6	Central de Ciclo Combinado do Pego	Power	Pego	742 714	Irregular	Natural Gas
PT.ES.7	Central Termolétrica Lares	Power	Lares	668 646	Irregular	Natural Gas
PT.ES.8	Industria Mineral - Prod Cales não Hidraulicas	Cement	Alcanede	384 566	Growing	
PT.ES.9	Fábrica Maceira-Liz	Cement	Maceira-Liz	354 069	Growing	
PT.ES.10	About The Future	Paper & pulp	Setúbal	1307 000	Stable	Biomass
PT.ES.11	Fábrica Cibra-Pataias	Cement	Pataias	266 971	Irregular	
PT.ES.12	Soporcel	Paper & pulp	Figueira da Foz	440 192	Growing	Biomass
PT.ES.13	Soporcel Pulp	Paper & pulp	Figueira da Foz	386 808	Growing	Biomass
PT.ES.14	Santos Barosa - Vidros, S.A	Glass	Marinha Grande	135 476	Irregular	Natural Gas
PT.ES.15	Central de Cogeração do Barreiro	Power	Lavradio	119 883	Irregular	Natural Gas
PT.ES.16	Fábrica da Marinha Grande	Glass	Avintes	88 572	Falling	Natural Gas
PT.ES.17	Verallia Portugal, S.A.	Glass	Figueira da Foz	88 515	Growing	Natural Gas
PT.ES.18	Gallovidro, s.a.	Glass	Marinha Grande	80 650	Stable	Natural Gas
PT.ES.19	Celbi	Paper & pulp	Figueira da Foz	1040 000	Stable	Biomass
PT.ES.20	Caima - Indústria de Celulose	Paper & pulp	Constância	231 000	Stable	Biomass

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Energy efficiency is the main decarbonisation alternative being considered, except for the cement sector and at the Pego coal power plant that are looking into the possibilities of fuel switch to biomass or increased fractions of biomass in the fuel mix. Given the recently approved National Strategy for Hydrogen, it is possible that some of the facilities will consider fuel switch to natural gas blended with hydrogen and other renewable fuels of non-biological origin, at a first stage, and to hydrogen in the longer term, as part of the decarbonisation process of the national gas grid.

4.3.2 CO_2 Storage possibilities

Seventeen storage units in deep saline aquifers were identified in the Lusitanian Basin, of which four units are located onshore and thirteen offshore (Figure 4-18). The level of geological information about the onshore and offshore units is very different, with better quality data available for the onshore, so that the four onshore storage units, with an estimated capacity of 340 Mt, are classified as Tier 2. The offshore units are classified as Tier 1 and, accordingly, the total storage capacity is much higher, 3975 Mt, but with implied higher uncertainty (Table 4-9).

Furthermore, the offshore storage capacity is unevenly distributed between the two geological formations that can act as reservoirs. The Lower Cretaceous Torres Vedras group in units PT.SU.5 to PT.SU.12 provide 3460 Mt capacity, while the Upper Triassic Silves Group units (PT.SU.13 to PT.SU.17) has a capacity of only 335 Mt, both at Tier 1 level. Onshore, in storage units PT.SU.1 to PT.SU.4, it is always the Silves Group that provides the storage capacity, ranging from 30 Mt for the smallest unit to 180 Mt to the largest unit (Figure 4-19).

Geographically, the four onshore units are within a radius of 30-40 km from each other and the storage unit “S. Pedro de Moel” (PT.SU.3) is actually in the coastal area, in direct continuity to the offshore storage unit.

The largest onshore storage unit “S. Mamede” (PT.SU.1), 180 Mt storage capacity, is sited in a low density area, but partly encompasses with an environmental protected area, the ”Serra de Aires e Candeeiros” natural park. Furthermore, topographic conditions are unfavourable as terrains is steep, with consequent increase in costs for building transport infrastructures.

The onshore storage units “Alcobaça” (PT.SU.2) and Alvorninha (PT.SU.4) deliver lower storage capacity, 80 Mt and 30 Mt, respectively, and although in areas with less environmental constraints, population density is higher than at “S. Mamede” and social acceptance may be a substantial issue in deciding if storage should be done in those units. The fourth onshore storage “S. Pedro de Moel” (PT.SU.3) has fewer constraints as it is located in a very low population density area, composed mostly of pine tree forests in flat terrain, with ideal conditions for geological / geophysical characterization and monitoring activities. The storage capacity is only 50 Mt, at Tier 2, but it is in geological continuity to the offshore storage unit “Q6-TV2” (PT.SU.12), and perhaps it can be jointly exploited with this offshore unit.

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The offshore storage units spread for more than 100 km parallel to the coastline and up to 50 km to the west of it. The storage complex often includes for each location, two potential reservoirs, the Lower Cretaceous siliciclastic deposits of the “Torres Vedras Group” and again Upper Triassic “Silves Group”. The former has undoubtedly better reservoir properties, but uncertainty is higher about the cap-rock quality, while the former is more heterogenous, with higher uncertainty about the injectivity, but the cap-rock is excellent.

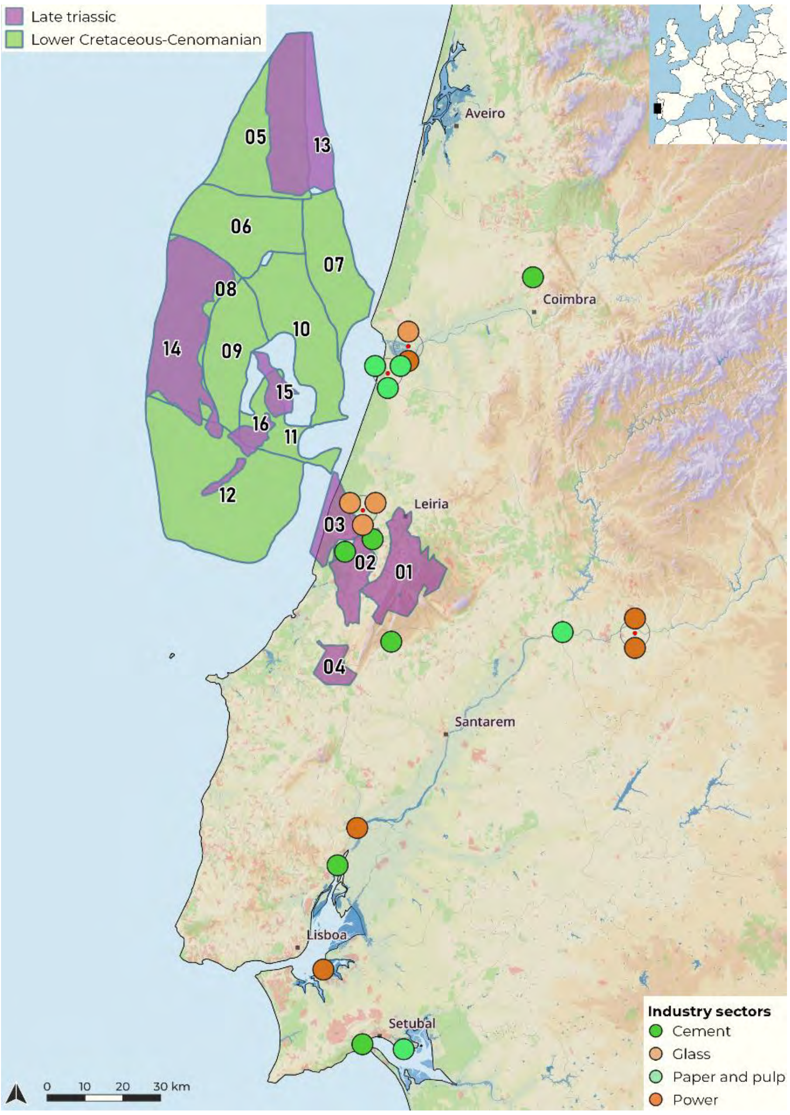

Figure 4-18 Potential storage units in the Lusitanian basin. Numbers represent the *unit ID* in Table 4-9. For detail see map in Appendix I.

If further characterisation confirms that the quality of the seal for the “Torres Vedras Group” is good, the offshore storage units “Q6-TV2” (PT.SU.12), “Q4-TV1” (PT.SU.7) and “Q3-TV4” (PT.SU.10), with storage capacities of 1020 Mt, 330 Mt and 710 Mt would be the preferable offshore storage units for the Lusitanian basin, given the large capacity and proximity to the coast line.

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With respect to the location of the sources, the onshore storage units are centrally located to several of them, in particular the cement and the glass sector sources in the “Marinha Grande” area. However, important sources, such as the Pego CCGT plant (60+ km), the Cement plant and Paper & Pulp mill at Setúbal (130+ km), or the cement plant at Souselas (80+ km) are quite distant from the storage sites. Distance to the offshore storage units is necessarily larger, but the most relevant storage units are near the shoreline and it is not discarded the possibility that horizontal wells, drilled from the onshore, can be used to store in the offshore formations.

Under any circumstances, and despite the inevitable decrease in estimated storage capacity for higher tier assessments, the Lusitanian Basin has more than enough capacity, onshore and offshore, for the expected demand for geological storage, given that the national strategy relies mostly on CO_2 utilization in connection to the hydrogen industry and geological storage is likely to be required only in some specific sectors (see section 4.3.4).

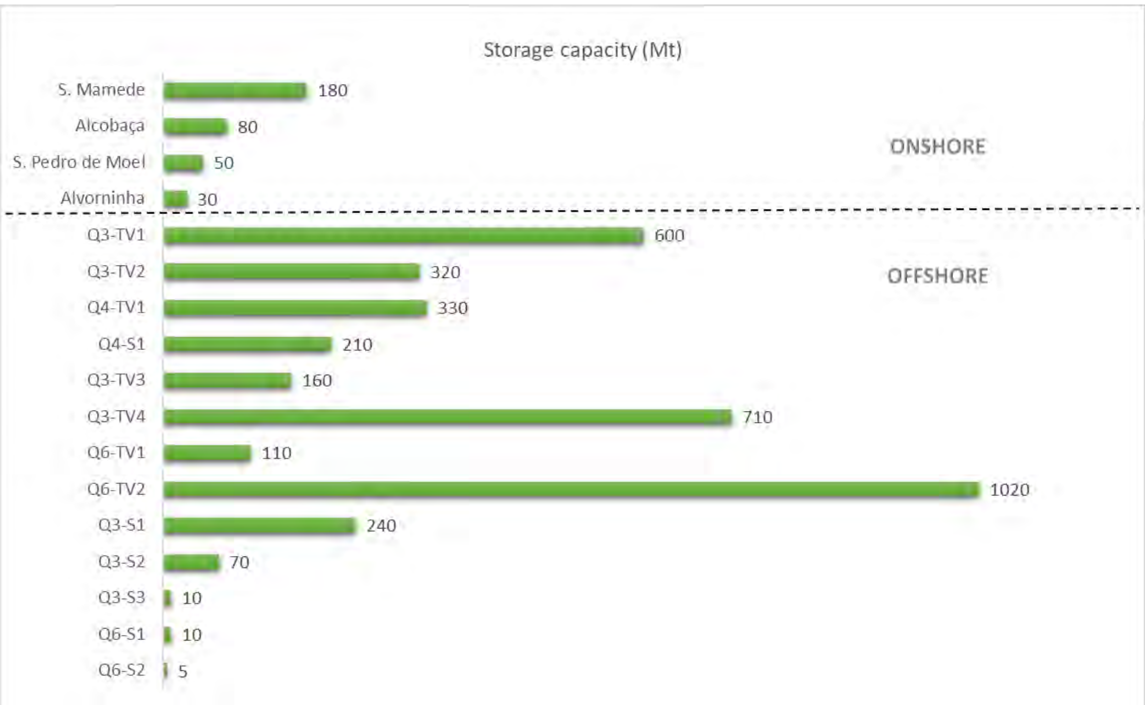

Figure 4-19 Distribution of storage capacity per storage unit.

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Table 4-9 Main features of potential storage units in the Lusitanian basin

Storage Unit ID	Storage type	Storage_Unit	Daughter unit	Formation	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)
PT.SU.1	DSA	Penela and Castelo Viegas Formations	S. Mamede	Silves Group	Sandstones and conglomerates	Onshore	2408	1300	180
PT.SU.2	DSA	Penela and Castelo Viegas Formations	Alcobaça	Silves Group	Sandstones and conglomerates	Onshore	2079	1234	80
PT.SU.3	DSA	Penela and Castelo Viegas Formations	S. Pedro de Moel	Silves Group	Sandstones and conglomerates	Onshore	2300	802	50
PT.SU.4	DSA	Penela and Castelo Viegas Formations	Alvorninha	Silves Group	Sandstones and conglomerates	Onshore	2600	873	30
PT.SU.5	DSA	Torres Vedras Formation *	Q3-TV1	Torres Vedras Group	Sandstones	Offshore	978	327	600
PT.SU.6	DSA	Torres Vedras Formation *	Q3-TV2	Torres Vedras Group	Sandstones	Offshore	1035	274	320
PT.SU.7	DSA	Torres Vedras Formation *	Q4-TV1	Torres Vedras Group	Sandstones	Offshore	897	349	330
PT.SU.8	DSA	Torres Vedras Formation *	Q4-S1	Torres Vedras Group	Sandstones	Offshore	1068	237	210
PT.SU.9	DSA	Torres Vedras Formation *	Q3-TV3	Torres Vedras Group	Sandstones	Offshore	1021	303	160
PT.SU.10	DSA	Torres Vedras Formation *	Q3-TV4	Torres Vedras Group	Sandstones	Offshore	960	369	710
PT.SU.11	DSA	Torres Vedras Formation *	Q6-TV1	Torres Vedras Group	Sandstones	Offshore	922	365	110
PT.SU.12	DSA	Torres Vedras Formation *	Q6-TV2	Torres Vedras Group	Sandstones	Offshore	1109	341	1020
PT.SU.13	DSA	Penela and Castelo Viegas Formations	Q3-S1	Silves Group	Sandstones and conglomerates	Offshore	2109	387	240
PT.SU.14	DSA	Penela and Castelo Viegas Formations	Q3-S2	Silves Group	Sandstones and conglomerates	Offshore	2258	216	70
PT.SU.15	DSA	Penela and Castelo Viegas Formations	Q3-S3	Silves Group	Sandstones and conglomerates	Offshore	2330	245	10
PT.SU.16	DSA	Penela and Castelo Viegas Formations	Q6-S1	Silves Group	Sandstones and conglomerates	Offshore	2395	352	10
PT.SU.17	DSA	Penela and Castelo Viegas Formations	Q6-S2	Silves Group	Sandstones and conglomerates	Offshore	2461	403	5

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4.3.3 Spatial conditions for cluster and network development

The spatial arrangement of sources in the Lusitanian basin, with respect to each other and to the storage sites, invites to consider three clusters of sources (Figure 4-20). A first cluster is composed by the sources around Marinha Grande, including the cement factories “Fábrica Cibra-Pataias” (PT.ES.11) and “Fábrica Maceira-Liz” (PT.ES.9), three glass factories (PT.ES.14, PT.ES.16 and PT.ES.18), and extending to the “Industria Mineral - Prod Cales não Hidraulicas” Lime producing company (PT.ES.8), with a joint estimated capture potential of 1.2 Mt/y (Figure 4-21).

These sources are located on top or very close to the onshore storage units “Alcobaça” and “ S. Pedro de Moel”(PT.SU.2, PT.SU.3), with the exception being the Lime factory, which is around 30 km from the other sources (Figure 4-20). The cement and lime plants are in rural setting and space problems are not anticipated for building capture facilities, but the situation is different for the glass factories, all of which are within the urban limits of Marinha Grande. The location of a consolidation hub could be set near one of the cement plants, depending on the chosen onshore storage unit. If the “Alcobaça” storage unit is first selected, the hub could coincide with the injection site. If the coastal storage unit “S. Pedro de Moel” is chosen, the same hub could collect the CO_2 from the more distant Lime factory, before trunk transport is done to the storage place.

A second cluster of sources can be defined around Lisbon and Setúbal and encompassing “About the Future” Paper & Pulp mill (PT.ES.10), the “Outão” (PT.ES.5) and “Alhandra” (PT.ES.2) cement plants and the “Ribatejo” (PT.ES.4) and “Barreiro” (PT.ES.15) power plants, totalling emissions of 3.07 Mt/y . These five sources are spread along a 40 km north-south alignment and are 80 km to 120 km distant from the onshore storage sites. The “Alhandra” cement factory is within an urbanised area and space constrains may exist to build new facilities. The sources are all located either in the Atlantic shoreline (for the sources in Setúbal) with dedicated port infrastructures, or along the Tagus estuary, and thus also very close to the Atlantic.

Multiple scenarios can be developed for collection of the CO_2 in this cluster, depending on whether trunk transport is through pipeline or ship (Figure 4-21) and if the purpose is utilisation or geological storage. For instance, a simple solution would be to use pipelines to collect CO_2 from all sources to a hub near “Alhandra” or “Ribatejo” sources and then a pipeline for trunk transport to utilization or to onshore storage sites. A more versatile solution could use ships and barges to transport CO_2 from “Outão”, “About the Future” and “Barreiro” sources to a hub near “Alhandra” or “Ribatejo” sources, where a CO_2 trunk pipeline could follow the corridor of the existing natural gas pipeline to transport CO_2 to utilization sites or to the onshore storage sites.

Several other scenarios are possible (such as using ships to transport to a port near the onshore sites, for instance Peniche port, and then utilise a trunk pipeline for onshore storage) and should be considered in WP5 of STRATEGY CCUS.

The third cluster is located around Figueira da Foz and Coimbra, with three Paper & Pulp mills (“Soporcel” (PT.ES.12), “Soporcel Pulp” (PT.ES.13) and “Celbi (PT.ES.19)), one CCGT power plant (“Lares”, PT.ES.7), one glass factory (“Verallia Portugal, S.A”, PT.ES.17) and one cement plant (“Souselas”, PT.ES.3), although the latter is about 30 km distant from the other sources (Figure 4-20). Together these sources emit 3.53 Mt/y, but the bulk of the emissions is from the power plant and the cement plant

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(and the “Celbi “Paper & Pulp mill, although mostly from biomass combustion). Considering the spatial arrangement of the sources and the distribution of emissions, the only alternative for collection to a hub seems to be by pipeline, the longest one being to transport from “Souselas” plant to a hub located near the other sources. Admitting the final destination would be geological storage, options for trunk transport depends on storage units being onshore or offshore. If storage is onshore, a 40 km – 50 km pipeline should be used as trunk transport to the injection sites. If offshore transport is to be considered, the hub could be placed near the “Figueira da Foz” port, from which either ships or offshore pipelines could be used for trunk transport.

Finally, and although the Pego Coal Power Plant is scheduled to shut down in 2021, there is the perspective that the facility is converted to a biomass power plant. Furthermore, in the same industrial complex there is CCGT “Pego” (PT.ES.6) plant. The industrial complex is isolated and at about 60 - 70 km from the onshore storage sites, and between it and the storage sites, there is also the “Caima - Indústria de Celulose” (PT.ES.20) paper & pulp mill, with emissions of around 0.23 Mt/y. Given the volumes involved, and despite the existence of a dedicated rail terminal in the Pego complex, transport must be through pipeline, either to CO_2 utilization or the identified storage units.

A common assumption in the previous analysis is that onshore storage units would be the initial option for storage, as envisaged in the COMET and CCS-PT projects, since the costs for storage are much lower. However, social acceptance in the area needs to be considered and it may prove advisable to store offshore.

If such would be the case, WP5 scenarios need to consider the costs of trunk transport by ship or by offshore pipeline. None of the most promising offshore storage sites is very distant from the coast, so that travelling distance for ships from the nearby ports (Figueira da Foz, Lisboa and Setúbal) would not be very high (less than 150 km for the most distant port, Setúbal). Usually, transport by ship is costs effective *vis-a-vis* pipelines for long distances and small volumes. Since the sources at the Figueira da Foz and the Marinha Grande are just about 20 km from the offshore storage sites, it is expected that pipeline will be a cost-effective solution. The sources at Lisbon-Setúbal are at a larger distance and it is necessary to compare both transport modes from an economic perspective.

The geographical and geological continuity between the onshore and the offshore storage sites, imposes a further scenario. Although additional geological studies need to be made, it is possible to envisage a situation in which horizontal wells are drilled from the onshore “S. Pedro de Moel” site, which has a very low population density, to the offshore storage sites just adjacent. This situation would in a first instance take advantage of the 50 Mt storage capacity in the “S. Pedro de Moel” site and then on the much larger capacity in the “Q6-TV2” offshore storage unit.

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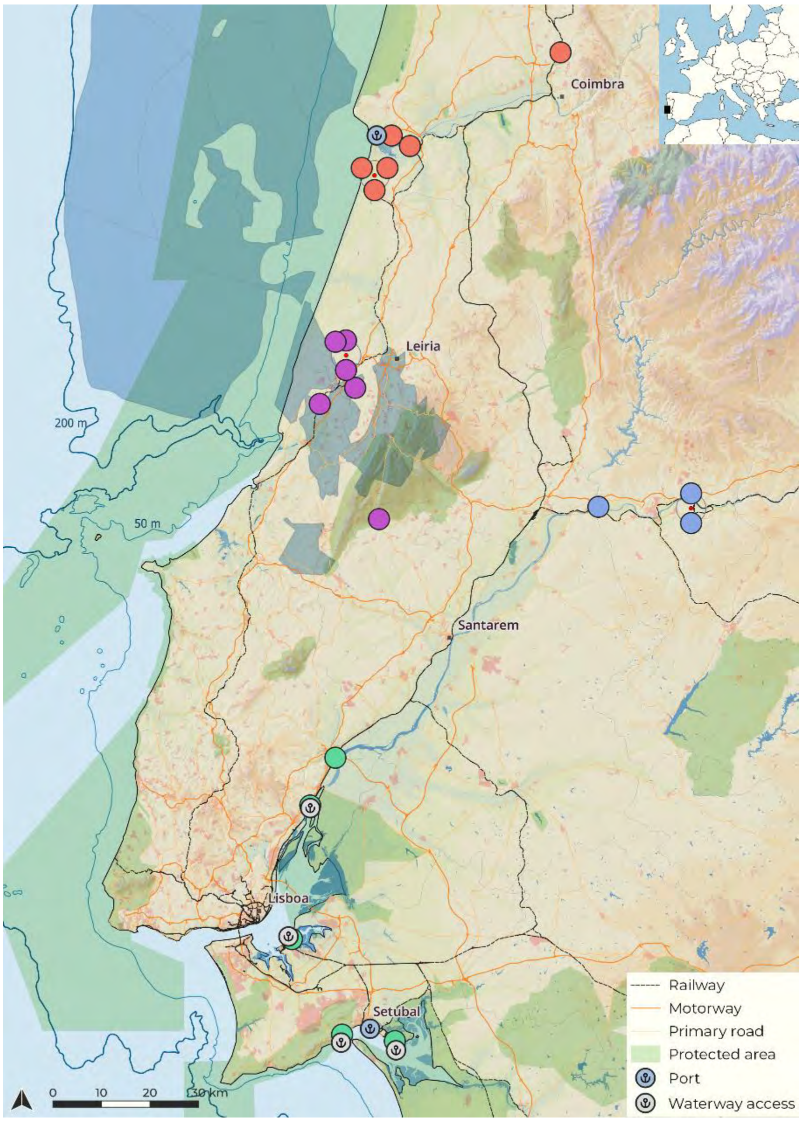

Figure 4-20 Clustering of CO_2 emitters and location of possible transport modes (roads, railways and ports).

4.3.4 CO_2 utilisation options

The overarching long-term strategy for energy and GHG emissions in Portugal is the Roadmap for Carbon Neutrality at 2050 (RNC2050), presented by mid-2019. CCUS does not appear as a solution in the RNC2050, mainly because the most cost-effective path to carbon neutrality that it proposed is based on deep electrification of nearly all end-uses, exclusively with renewable electricity. The utilisation of CO_2, besides the production of synthetic fuels, was not considered in the RNC2050 due to the lack of information at the time. Similarly, the capture of negative emissions from biomass was not considered. Biological carbon sinks in forests and pastures is foreseen, but not CCUS.

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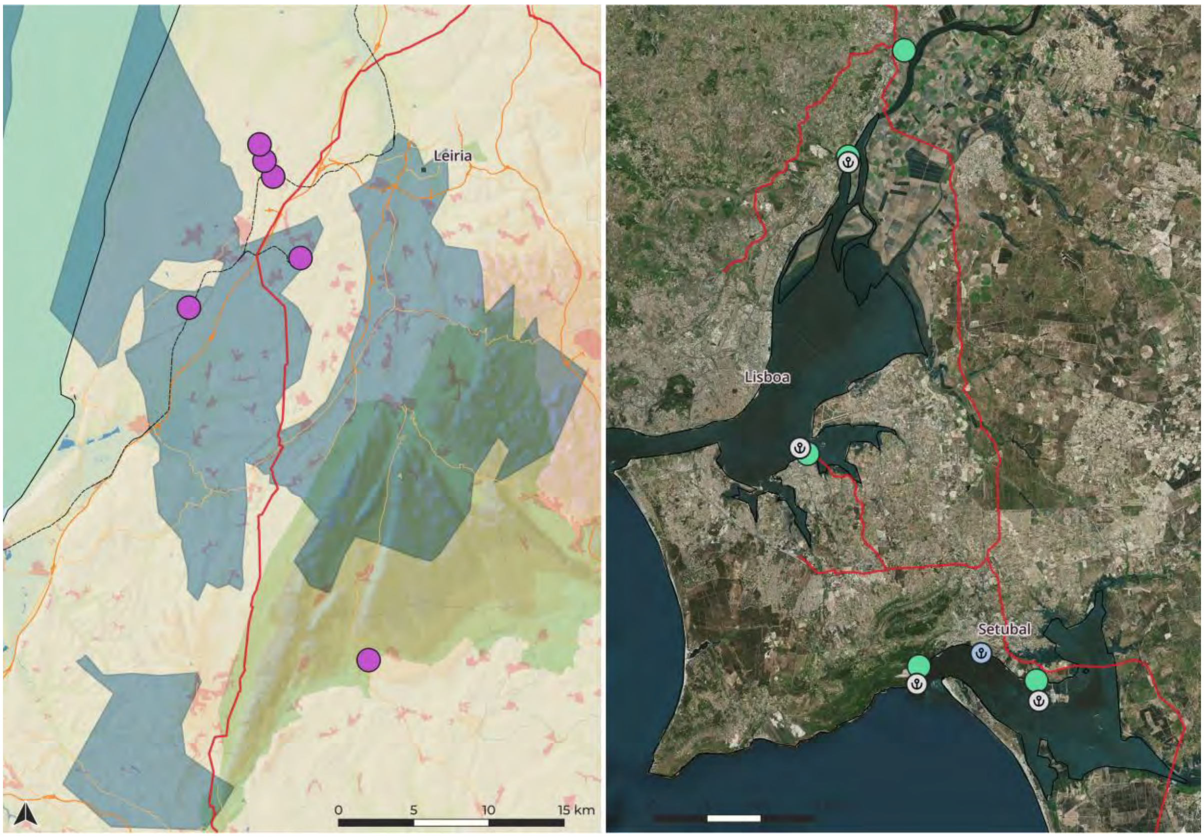

Figure 4-21 Left: Sources in the central cluster with respect to onshore storage sites. Right: Sources in the Lisbon and Setúbal area, also showing the location of ports and existing pipeline network.

At the end of 2019, the National Energy-Climate Plan 2021-2030 (NECP) was presented. It is aligned with the RNC2050 long-term strategy; therefore, it does not include CCUS.

Still, currently CO_2 has several industrial and commercial applications in Portugal:

- Industrial Applications: CO_2 is already used in some industries in Portugal to produce chemicals and as feedstock. Applications include: production of refrigeration systems, welding systems (inert gas protection), water treatment processes (to stabilize the pH of water) and carbonated beverages. It is also used in the metals industry to enhance the hardness of casting molds and as a welding agent. Carbon dioxide is found in various fire extinguishers (firefighting) and prevents oxygen from further fueling a fire (CO_2-based fire extinguishers effectively manage electrical fires and those caused by solvents, fuels and oils);
- Chemical and Pharmaceutical Applications: 1) urea (used as a fertilizer and in automotive systems and medicine), 2) methane; 3) methanol, 4) inorganic and organic carbonates (materials for the national automotive industry), 5) polyurethanes and sodium salicylate, 6) formic acid (e.g. WC Pato, F.Lima, J&J), 7) ammonia, 8) plastics and polymers when CO_2 is combined with epoxides, 9) water treatment, 10) dry ice to keep food cool, and to cool, pressurize and purge industrial equipments;

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- Electronic Applications (electronic equipment production): CO_2 is used in the electronics industry for circuit board assembly, to clean surfaces and in the manufacture of semiconductor devices;
- Greenhouses: CO_2 enrichment solution is also used and can help increase the harvest and growth rate of fruits, vegetables and vegetables, and greenhouse plants and flowers. The scope is to achieve optimal levels of carbon dioxide to stimulate flowering of plants, faster maturation of crops and crops with greater commercial value;
- Food & Beverage industry: CO2 is used to process animals like chickens and pigs, used as a bacteriostatic agent in MAP (modified atmosphere packaging), i.e., in products ranging from meat and poultry to dairy products such as cheese and milk powder, to pasta and bakery products, thus extending the shelf life of chilled and ambient products. It is also used in carbonated beverages (soft drinks, sparkling water, beer, etc.).

These existing uses are all small scale and without meaningful impact to climate change mitigation.

Meanwhile, a new vision for the future of the energy system had been slowly coming into the awareness of the technological community and the public administration, especially since mid-2018, when Portugal signed the 'Hydrogen Initiative'. Hydrogen can be seen as the missing link in a carbon neutral economy because it allows the integration of the energy system by promoting power and natural gas grids interconnection and renders CCUS (on its CCU branch) more effective. Hydrogen related technologies, by linking the fuels' system and the electricity system, allow to overcome some economic and technological barriers to electrification of the energy system, including too stranded assets, too high investment levels and security of supply issues related to interannual weather variability.

This process resulted in the launch of the National Strategy for Hydrogen (EN-H2) by August 2020. EN-H2 does not contradict the long-term vision for energy and emissions, nor does it modify the targets of RNC2050 and NECP, however it proposes a main technological path with significant differences to these documents. This path is still based on renewable electricity, but instead of being all used directly at end-use equipment, large amounts are directed to the production of renewable hydrogen and other renewable fuels of non-biological origin (RFNBO), in particular methane and aviation kerosene, as well as of certain chemicals to be used as raw matter by the industry, such as ammonia. For this process of producing RFNBO and other chemicals, carbon dioxide must be added to hydrogen. This CCU aspect stands more implicit than highlighted in EN-H2, however it is a technical necessity.

The quantities of RFNBO in EN-H2 imply around 1 Mt CO_2 capture by 2030 (essentially for methanation processes). Figure 4-22 depicts the essential data for CCU up to 2050 in the scope of the EN-H2. The mix of origins responds to certain criteria: for instance, capture of emissions by biomass thermal power plants has the highest priority, as they do not count for the country's GHG emissions and therefore can be used for assembling RFNBO with no implicit fossil context. Whereas emissions from fossil fuels or non-energy processes have the lowest ranking because they lead to just a transitory use of CO_2, which will end up in the atmosphere anyway.

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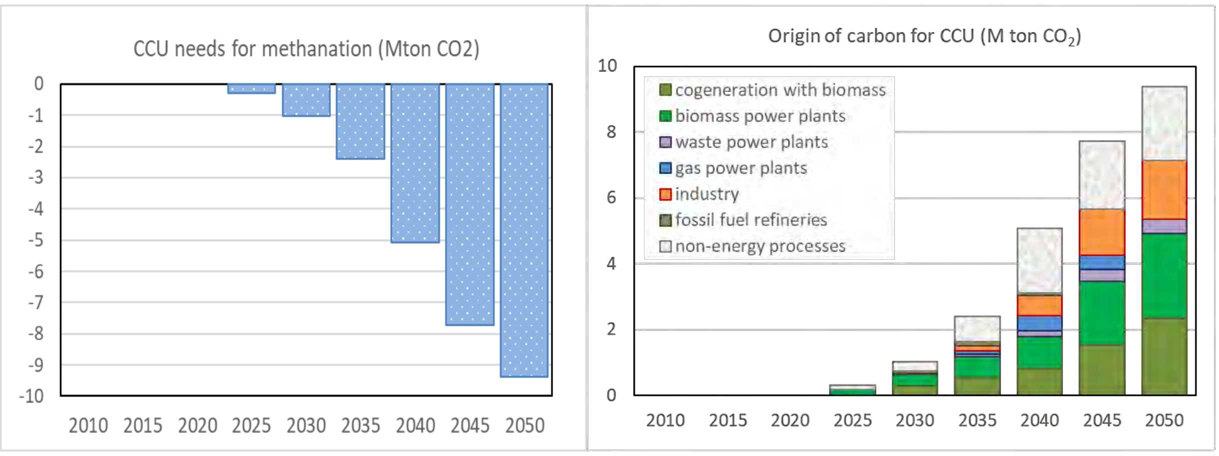

Figure 4-22 CCU needs and origins of CO_2 in the BASE Scenario for EN-H2 (DGEG, 2020).

Finally, it is relevant to remark that 'blue hydrogen' (reforming natural gas + CCS) is not considered in the EN-H2. On the one hand, a CCS infrastructure would need some years to develop; on the other hand, the very low prices of solar electricity in the country mean that obtaining renewable hydrogen by electrolysis already is cheaper than blue hydrogen (DGEG, 2020). So, the opportunity window for blue hydrogen and the related CCS in Portugal is very narrow, if it exists at all.

In conclusion, for Portugal, CCU is seen as essential at the current national energy plans, but not CCS.

Related to alternatives to storage in geological formations of CO_2 captured in the cement sector, there are some ongoing research efforts, from academia and the cement industry related to mineralisation:

- C&DW (Construction & Demolition Waste) (mineralisation): Use of CO_2 to carbonate C&DW and concrete recycling fines to improve their proprieties and facilitating their use as either artificial aggregates or supplementary cementitious materials (SCM). Ongoing studies in Portugal in this domain are being conducted by the Collaborative Laboratory **C5Lab** to determine maximum potential.
- Artificial Reefs (mineralisation): CO_2 fixation by artificial reef development in marine environment using carbonated materials. Mineral carbonation is an option for storage of carbon dioxide in industrial waste materials by converting it into carbonates similar to the end products of natural weathering processes. IPMA, the Portuguese Institute of the Sea and the Atmosphere, is leading that research.

4.3.5 Main features of technical potential for ICCUS development

The National Strategy for Hydrogen forecasts that, after 2025, large volumes of CO_2 will be required for methanation processes and synfuel production. Development of CCU clusters for capturing CO_2 will consequently become a requirement in the near term, with the focus being on the CO2 utilisation. The role for geological storage of CO_2 will be two-fold: i) as an intermediate short-term storage to deliver the CO_2 to the proposed utilisation; ii) in some industry sectors, for indefinite sequestration of the CO_2 in the geological formation.

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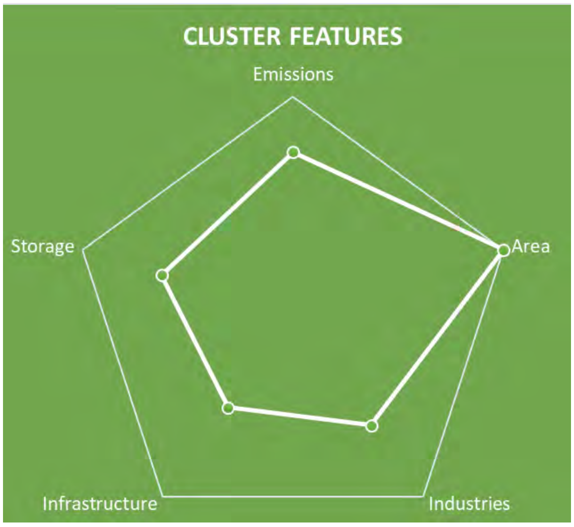
The high level of process emissions from the cement sector and the existence of several sources in a region near or even overlying the onshore storage sites, build the case for CCUS in the Lusitanian basin. Synergies of the cement plants with other sectors, such as Glass and Paper & Pulp can also be found due to the relatively proximity of facilities from those sectors. Successful implementation of the ICCUS cluster can lead to the expansion of a network to encompass those sources around the Lisboa and Setúbal industrial areas and the Figueira da Foz area, with focus on the cement and power sectors, but again on the Paper & Pulp sector.

The Paper & Pulp sector is relevant in the area and is mainly utilising energy from biomass combustion. There are five active plants in the Lusitanian basin, some of which are large-scale, emitting more than 1 Mt/y, and there is the likelihood that the Pego coal power plant will be reconditioned to run on biomass. The possibility for BECCS to be implemented in the Lusitanian basin in complement to the utilisation of CO_2, allowing for negative emissions, should not be discarded in these facilities running on biomass (or biomass fractions) or on biomass power plants to be built.

The onshore storage capacity is adequate to accommodate decades of the current emissions, but further storage capacity is available offshore, in geographic and geological continuity with the onshore storage locations, bringing added flexibility to the storage system.

The CO_2 collection and transport network is more likely to occur with a purposely-built pipeline network following along the same corridor as the existing natural gas pipelines, or along the paths defined by the COMET project. However, given that sources around Lisboa and Setúbal are either at shoreline or in the estuary of the Tagus, ships and barges can be also considered as alternatives for CO_2 collection to a consolidation hub. Trunk transport from that region can be done through pipelines to onshore storage sites or utilization sites, or by ships or a combination of pipelines and ships for offshores storage.



Aside from the CO_2 utilisations proposed in the EN-H2, the cement sector is also considering opportunities for utilisation of CO_2 in new building materials, such as CO_2-cured concrete, concrete blocks of different sorts or artificial aggregates, which can also be of interest.

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Table 4-10 Lusitanian Basin cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	Facilities spread along the coastal region, but with 3 main loci: Leiria District, Setúbal-Lisboa axis and Figueira da Foz.	+
	Emission volume distribution	Several large single point sources, especially in the cement sector, but also some in the power and paper & pulp sectors.	+
	Emission volume profile	One coal power plant closing, cement sector with a downward trend, but most sources with a stable trend.	-
	Emissions type and quality	The cement sector is an important emitter, with CO_2 process-related emission being relevant. CO_2 from biomass combustion important in Paper & Pulp but some smaller relevance in cement. No high concentration sources.	+
AREA	Industrial area character	Most sources in rural areas or within industrial complexes around cities. Glass sector within urban areas.	+
	Importance of industry	Glass and cement sector main industrial activities in central Portugal. Paper & Pulp very important in the region of Figueira da Foz and Setúbal.	+
	Cluster recognition	Area had previously been included as clusters in COMET project, with storage in a first phase onshore and progressing later to offshore.	+
INDUSTRIES	Integration of industry	Poor integration between individual sources, but cement factories owned by only two companies. Paper & pulp plants also property of two companies.	-
	Decarbonisation alternatives	Mostly Energy Efficiency or switch to biomass. Switch to hydrogen has been gaining attention. Less possibilities in the cement sector, although ongoing studies for fuel switching to a high temperature thermal input of biomass, hydrogen and plasma (electrification) mix for the kiln and precalciner.	+
	CCU	Potential for CO_2 usage for producing synthetic fuels. Given the relevance of cement sector, uses of CO_2 in building materials should be considered.	+
	Motivation for decarbonisation	National strategies for climate change mitigation	~
	Motivation for CCS	An alternative for excess CO_2 that cannot be used and/pr result from process relate emissions. Intermediate storage a requirement for large-scale utilisation.	~
INFRASTRUCTURE	CO_2 collection options	Sources are connected to natural gas pipelines which could be used as the corridor for CO_2 pipelines. Ships and barges could be an alternative for collection from the sources around Lisboa and Setúbal.	+
	CO_2 consolidation options	No anticipated spatial difficulties for implementing consolidation hubs.	+
	Existing CO_2 infrastructure	No existing infrastructure.	–
	Infrastructure reuse options	Existing natural gas pipelines likely to continuing running methane (in the future with an hydrogen blend), unlikely to be available for reuse.	-
STORAGE	Storage accessibility	Onshore sites are easily accessible for sources in the Leiria cluster, but more distant from the other sources, up to 120 km. Offshore storage is very close to the shoreline, easily accessible.	~
	Storage capacity	Onshore capacity should be sufficient, but offshore capacity is much larger.	+
	Storage flexibility	Adequate, since the onshore storage sites are very close and there is additional storage capacity provided by the offshore sites.	+
	Storage development integration	No organisation has put forward plans for developing storage.	-

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4.4 Northern Croatia

4.4.1 Emissions and industry sectors

The Northern Croatia promising region comprises ten emission sources (Figure 4-23), with two other sources outside the region being considered, since they have good connection for transport to Northern Croatia and because they are the only sources with emissions above 1 Mt/y: “TE Plomin” coal power plant, (HR.ES.11), and Rijeka refinery “Rafinerija nafte Rijeka” (HR.ES.12), with CO_2 emissions of 1.2 Mt/y and 1.0 Mt in 2018, respectively (Table 4-11 and Figure 4-24). Six power plants and two refineries define the dominating sectors, both in the number of facilities, and in the percentage of emissions, accounting for 67% of the emissions in the area (Figure 4-23).

Other industrial sectors are represented by a single facility, although in some cases with important emissions, particularly the cement plant at Našice (HR.ES.2), which emitted 0.65 Mt CO_2 in 2018 and the “ Proizvodnja gnojiva” fertilizer production (HR.ES.1) at Kutina, with emissions of 0.75 Mt/y. The oil & gas processing sector has one important facility at Virje, the Molve NGPP (HR.ES.5), with emissions of 0.29 Mt/y. There is also a glass production facility (HR.ES.5), with emissions just above 0.1 Mt/y.

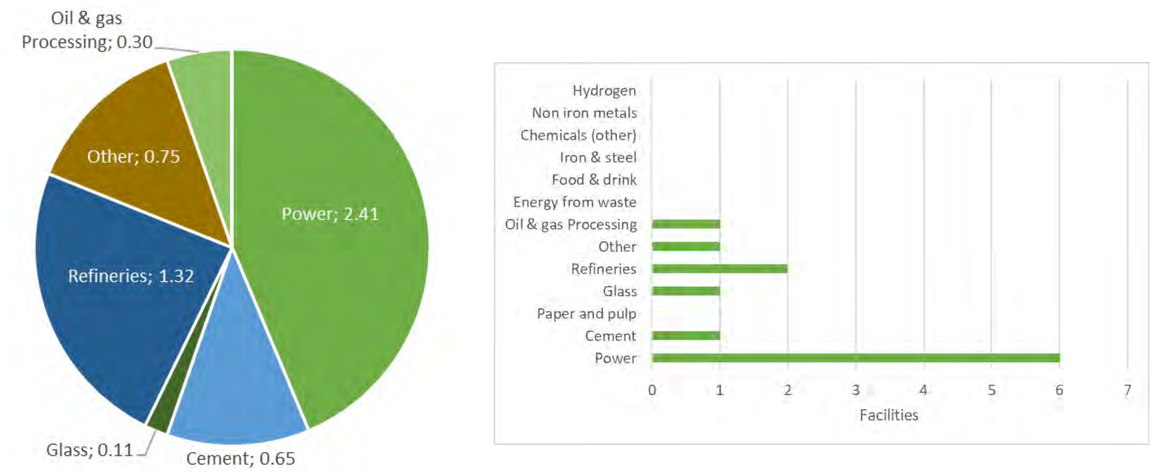
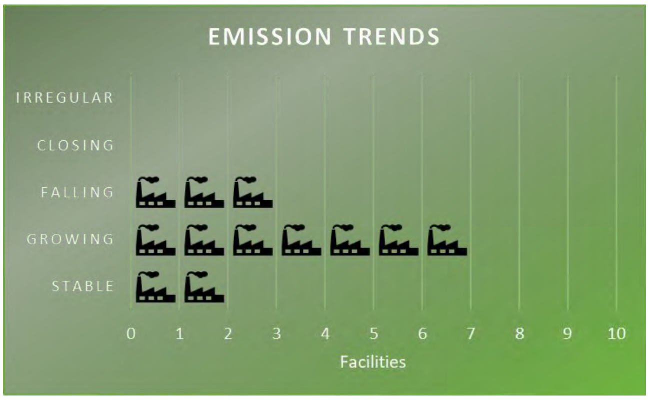


Figure 4-23 Emissions (in Mt/y) and facilities per sector in Northern Croatia.



Overall, the sources are quite dispersed across Northern Croatia, with Zagreb and Sisak being the only cities where there is more than one source, at Zagreb the “TE-TO Zagreb” (HR.ES.3) and the “EL-TO Zagreb” (HR.ES.7) power plants, and at Sisak the “TE-TO Sisak” power plant (HR.ES.6) and “Rafinerija nafte Sisak” refinery (HR.ES.4). All other sources are isolated and tens of kms distant from any other sources.

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No high CO_2 concentration sources were inventoried in Northern Croatia, with concentrations ranging from 4% to 16%, the highest being at the cement plant at Našice.

The emission trends for seven sources have been increasing, with some of the larger sources, such as the cement plant, the Rijeka refinery and the Zagreb "TE-TO Zagreb" natural gas power plant showing a "growing" trend, with "Competition" being the main driver. Apart from the Sisak refinery, where operation are scheduled to phase-out (with facilities possibly being converted for bitumen production), two other facilities show a "Falling" trend in emissions, "EL-TO" Zagreb", and the third largest emitter in the area, the fertilizer production "Proizvodnja gnojiva" with the main driver being "consumer behaviour". The largest CO_2 emitter in the region, the "TE Plomin" coal power plant shows a stabilised trend in emissions (Table 4-11).

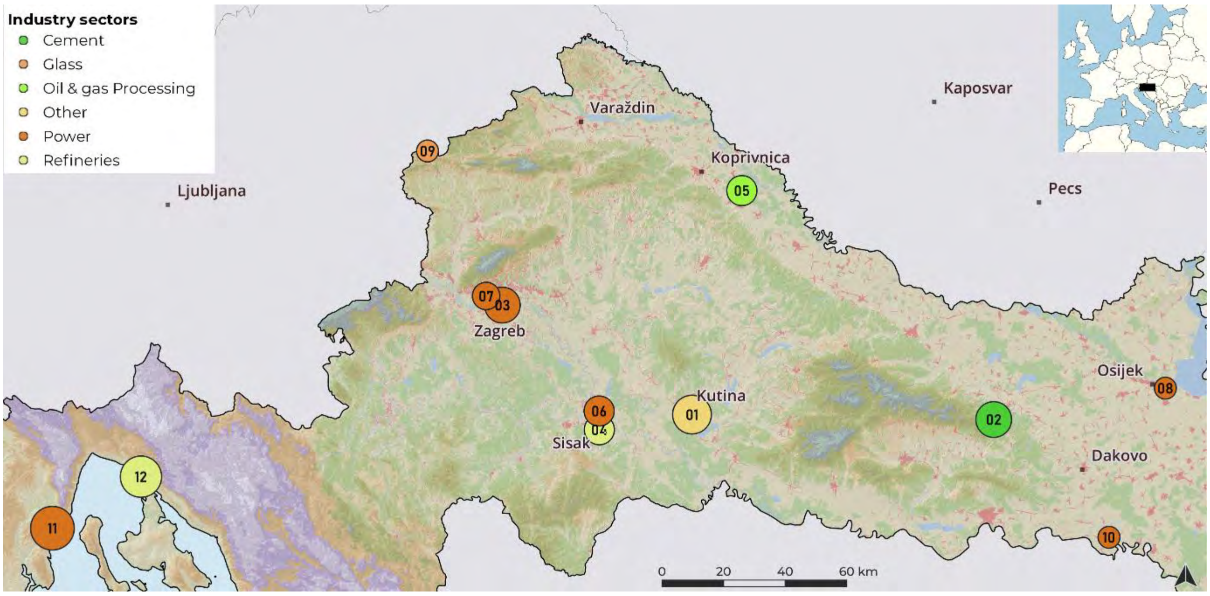

Figure 4-24 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-11. For detail see map in Appendix I.

Natural gas is the main fuel utilised, except for the coal power plant and the biomass cogeneration power plant "Kogeneracijsko postrojenje Viridas Biomass" (HR.ES.10). Refinery gas and other gases are used as fuels in the Rijeka and Sisak refineries, while the cement factory utilises petroleum coke, coal and natural gas (Table 4-11).

The number of emissions points is very high in the Sisak refinery (19 emission points) and at the gas processing facility at Virje (14 emission points), increasing the difficulty and costs for implementing CO_2 capture. No indication is provided about the number of emission points at the Rijeka refinery, but it is likely to be high. In all other sources, the number of emission points varies from 1 (the cogeneration biomass plant) to 6 (the "TE-TO Zagreb)".

CO_2 produced from biomass combustion is obviously the predominant in the cogeneration power plant at Babina Greda (HR.ES.10), but may also be important at the "TE-TO Sisak" power plant in Sisak and at the "TE-TO Osijek" power plant, since both use biomass in the fuel mix.

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Table 4-11 Main features of CO_2 emitting facilities in Northern Croatia

Emitter ID	Facility name	Sector	City	Emissions (tCO_2/y)	Emission trend	Main fuel
HR.ES.1	Proizvodnja gnojiva	Other	Kutina	750 249	Falling	Natural gas
HR.ES.2	Našicecement d.d.	Cement	Našice	645 090	Growing	Petroleum coke, coal and natural gas
HR.ES.3	TE-TO Zagreb	Power	Zagreb	550 601	Growing	Natural gas
HR.ES.4	Rafinerija nafte Sisak	Refineries	Sisak	312 067	Falling	Refinery gas & other gases
HR.ES.5	Objekti prerade plina Molve	Oil & gas Processing	Virje	295 235	Growing	Natural gas
HR.ES.6	TE-TO Sisak	Power	Sisak-Caprag	283 848	Growing	Natural gas
HR.ES.7	EL-TO Zagreb	Power	Zagreb	209 610	Falling	Natural gas
HR.ES.8	TE-TO OSIJEK	Power	Osijek	109 982	Growing	Natural gas
HR.ES.9	Vetropack Straža d.d.	Glass	Hum na Sutli	105 882	Stable	Natural gas
HR.ES.10	Kogeneracijsko postrojenje Viridas Biomass	Power	Babina Greda	102 169	Growing	Biomass
HR.ES.11	TE Plomin	Power	Plomin	1 157 609	Stable	Coal
HR.ES.12	Rafinerija nafte Rijeka	Refineries	Kostrena	1 004 676	Growing	Refinery gas & other gases

The cement sector is where process induced emissions are most relevant, with 65% of the emissions not related to fuel combustion, but it is possible that the fertilizer facility “Proizvodnja gnojiva” also has an important component of process emissions.

4.4.2 CO_2 Storage possibilities

The storage capacity in Northern Croatia is provided by two Tier 1 Deep Saline Aquifers storage units and by Tier 2 Hydrocarbon Fields storage units, in all cases on an onshore setting.

DSA Drava (HR.SU.5) and DSA Osijek (HR.SU.6), both defined in the Drava Depression in the eastern part of the promising region, have an estimated Tier 1 storage capacity of 2049 Mt CO_2 (Table 4-12). These two aquifers are well located with respect to the NGPP Molve, the cement factory at Našice and the “TE-TO OSIJEK” power plant, and at about 40 km from the Biomass power plant at Babina Greda (Figure 4-26).

The deep saline aquifers in the Sava Depression, DSA Poljana (HR.SU.2), DSA Okoli (HR.SU.3) and DSA Iva (HR.SU.4), are actually units of the Sava Depressions, and present a joint storage capacity of 536 Mt. These three DSAs are located in the centre of the study region, at distances less than 20 kms to the remaining sources, except for the Rijeka refinery and the TE Plomin coal power plant, which are at 170 km and 140 km distance. The glass factory is also at around 60 km (Figure 4-3).

The storage units DSA Poljana, DSA Okoli and DSA Iva are geographically coincident, although at different depth levels. This arrangement can be particularly favourable for the flexibility of the storage system, with the highest capacity formations (Poljana and Okoli, each with more than 200 Mt), compensating for the smaller capacity site (Iva, with 55 Mt).

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Given that the emission levels in the twelve operational sources is 5.53 Mt/y, and although assessments for Tier 3 and Tier 4 retrieve lower storage capacities, especially for the Drava and Osijek DSAs, it is likely that here is enough storage capacity in the deep saline aquifers to meet the maximum possible demand of CO_2 capture in the region.

Hydrocarbon fields present another storage opportunity in Northern Croatia, with seven fields producing oil and seven other producing natural gas. The full storage capacity in the fourteen fields amounts to 144 Mt, based on the total recoverable volume of oil/gas under reservoir conditions, and considering that CO_2 could replace the volume that was previously occupied by the HC in the reservoirs. Several of the producing fields are almost depleted. In fact, the Bokšić (HR.SU.18) and Legrad (HR.SU.19) fields should stop production already in 2021, while the Okoli field (HR.SU.10) will be depleted by 2023 (Table 4-12).

Geographically, the hydrocarbon fields overlap those of the deep saline aquifers, since many of them are rooted in the same Sava stratigraphic group, increasing the flexibility of a storage system.

There is a group of nine hydrocarbon fields located in Eastern Croatia, with a full capacity of 113 Mt, and a second group of five fields in Central Croatia, with a capacity estimated at 31 Mt. These capacities are considerable and, most of all, reflect a higher level of confidence in the storage adequacy of the formations, as containment conditions are proved and knowledge on the geological conditions are much higher than for the DSA. Hence, the hydrocarbon fields are likely to be the initial preferential targets in the Croatian promising region.

Still, storage capacity in the hydrocarbon fields are asymmetrically distributed, particularly in Eastern Croatia with only two fields providing 74 Mt capacity, the Molve (HR.SU.14) and Kalinovac (HR.SU.15) fields. Capacity in all other fields in Eastern Croatia range from 3 Mt to 13 Mt. The storage capacity in the five Central Croatia fields ranges from 2 Mt to 10 Mt (Figure 4-25).

Field availability will obviously vary, and although some fields are expected to become available for CO_2 injection in 2021, most of them will only stop production after 2030. Thus, the alternative for storage in this fields is CO_2-EOR (see section 4.4.4), which as a matter of fact is already commercially ongoing in Croatia.

Figure 4-25 Distribution of storage capacity per storage unit.

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Table 4-12 Main features of potential storage units in Northern Croatia

Storage Unit ID	Storage type	Storage_Unit	Daughter unit	Formation	Lithology	Setting	Depth to top (m)	Thickness (m)	Storage capacity (Mt)	Field availability
HR.SU.2	DSA		DSA Poljana	Klostar Ivanic Fm	Sandstone	Onshore	1450	150	251.6	
HR.SU.3	DSA		DSA Okoli	Ivanic Grad Fm	Sandstone	Onshore	2000	250	229.0	
HR.SU.4	DSA		DSA Iva	Ivanic Grad Fm	Sandstone	Onshore	2050	250	55.1	
HR.SU.5	DSA	DSA Drava		Sava Group	Sandstone	Onshore	900	1000	1938.9	
HR.SU.6	DSA	DSA Osijek		Vinkovacka Fm	Sandstone	Onshore	1000	500	109.9	
HR.SU.7	DHF	Klostar		Klostar	Sandstone/Granite	Onshore	973	NA	2.7	2027
HR.SU.8	DHF	Ivanic		Ivanic	Sandstone	Onshore	1619	NA	5.5	2032
HR.SU.9	DHF	Zutica		Zutica	Sandstone	Onshore	1699	NA	10.1	2032
HR.SU.10	DHF	Okoli		Okoli	Sandstone	Onshore	1750	NA	7.3	2023
HR.SU.11	DHF	Struzec		Struzec	Sandstone	Onshore	727.15	NA	1.7	2040
HR.SU.12	DHF	Lipovljani		Lipovljani	Sandstone	Onshore	1026.12	NA	3.2	2023
HR.SU.13	DHF	Gola Duboka			Carbonate	Onshore	2520.76	NA	5.8	2030
HR.SU.14	DHF	Molve			Breccia/Carbonates/Metamorphic rocks	Onshore	3100	NA	42.8	2027
HR.SU.15	DHF	Kalinovac			Carbonates/Metamorphic rocks	Onshore	3054	NA	31.6	2035
HR.SU.16	DHF	Stari Gradac			Clastics/Carbonates/Metamorphic rocks	Onshore	3450	NA	3.5	2035
HR.SU.17	DHF	Benicanci		Benicanci	Carbonate breccia	Onshore	1700	NA	8.8	2035
HR.SU.18	DHF	Boksic		Boksic	Sandstone	Onshore	1519	NA	13.6	2021
HR.SU.19	DHF	Legrad			Sandstone	Onshore	1635	NA	4.1	2021
HR.SU.20	DHF	Sandrovac			Sandstone	Onshore	750	NA	2.9	2037

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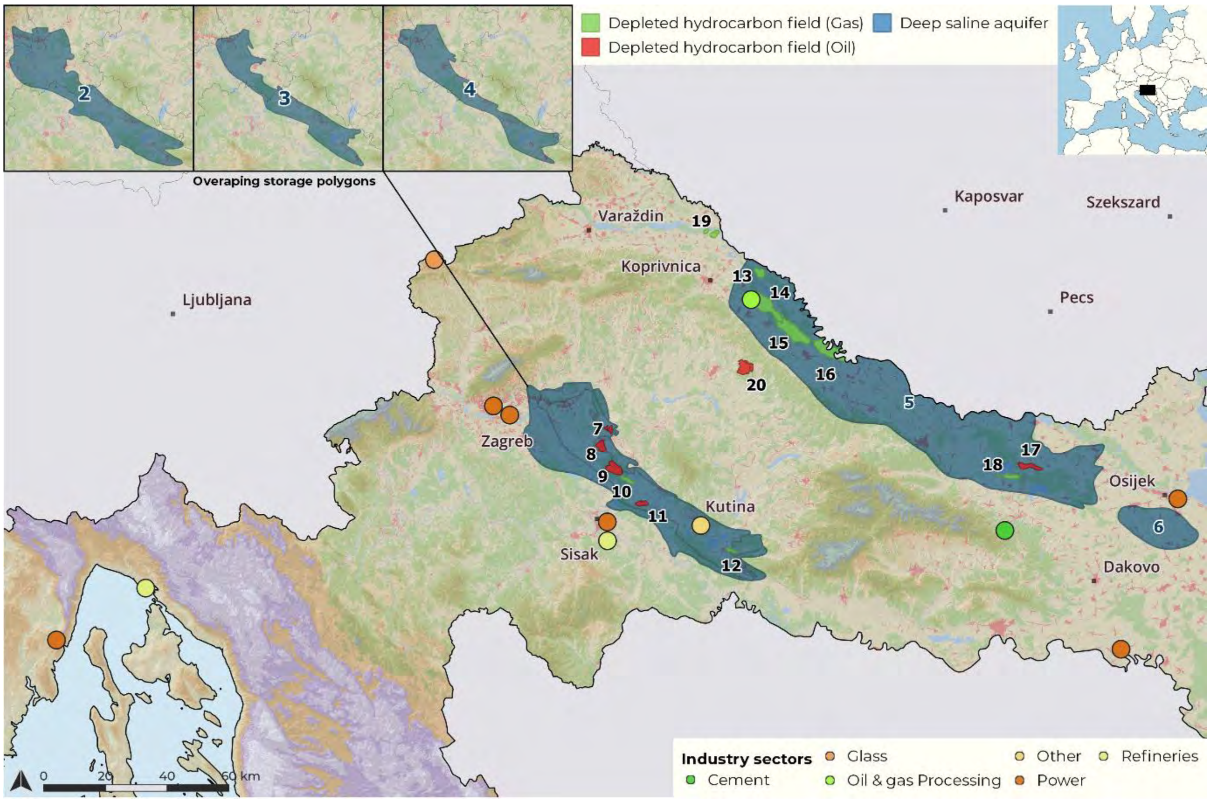

Figure 4-26 Potential storage units in Northern Croatia. Numbers represent the *unit ID* in Table 4-12. For detail see map in Appendix I.

4.4.3 Spatial conditions for cluster and network development

In Northern Croatia the spatial distribution of sources advises to consider three clusters: the Eastern cluster, the Central cluster and the Adriatic cluster (Figure 4-27).

The sources in the Eastern cluster are the cement factory, the biomass plant and the Osijek Power plant, which jointly emit about 0.86 Mt/y. These sources are all located in rural areas and no major issues about space for building capture facilities is anticipated. Consolidation hubs do not seem to be necessary for this cluster, since the most obvious candidates for CO_2 injection are the CO_2-EOR candidate field Beničanci (HR.SU.17) and depleted natural gas field Bokšić (HR.SU.18), with a total storage capacity of 23 Mt, enough to store several years of the emissions from the three sources. These fields are located 18 km to 65 km from the sources in the cluster, but with a spatial arrangement that does not require for a consolidation hub right until the injection site.

The cement plant and the Osijek power plant in this cluster are connected to the operational natural gas pipeline network and transport by pipeline using the same corridor is an option since the pipeline also goes to the Bokšić and Beničanci hydrocarbon fields (Figure 4-28). The cement plant and the Osijek power plant also have railway terminals, but railways are not going towards the areas where the hydrocarbon fields are located.

The biomass power plant at Babina Greda is not connected to the natural gas pipeline network, nor to the railway network. Transport options seem to be roads or purposely built pipeline. Given the

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small amounts of CO_2 produced (0.1 Mt/y) transport by road should be considered in the techno-economic scenarios.

The Central cluster includes seven sources which together emit 2.5 Mt/y. The cluster is spread geographically in an area of about 8500 km^2, with the Molve power plant quite distant from any other source. All sources in the cluster are either located in rural areas or within industrial complexes, so that no problems of space for building capture facilities is likely to occur. The exception seems to be EL-TO Zagreb power plant, which is within the city limits, hence with higher challenges for building new facilities and for transport while within the city limits.

Two scenarios of consolidation hubs for collecting CO_2 from the Central cluster can be envisaged. A first scenario considers two hubs. The first hub is located near Ivanja Reka (Zagreb area), gathering CO_2 from the glass factory, TE-TO Zagreb and EL-TO Zagreb power plant. Although most sources in the cluster are connected to the natural gas pipeline, that does not occur for the two power plants in the Zagreb city limits. For the glass factory at Hum na Sutli, some 50 kilometers North from Zagreb, and given the low level of CO_2 emissions (0.1 Mt/y), transporting in liquid phase by road might be an option to consider. Trunk transport from the hub to the storage sites could then follow the pipeline corridors of the existing natural gas network.

The other hub is located near Stružec (15 km from Sisak), gathering CO_2 from the Sisak Refinery, the TE-TO Sisak power plant, the fertilizer production plant and the Molve NGPP. In this case, collection of CO_2 to the hub could follow the existing pipeline, as all sources are connected to it.

CO_2 is expected to be trunk transported by pipeline from the hubs in this cluster to storage sites in the western part of Sava depression, firstly to be injected in oil reservoirs for EOR operations (HR.SU.7, HR.SU.8, HR.SU.9, HR.SU.11, HR.SU.12), in connection to the ongoing CO_2 EOR projects in that area. In a second phase, the transport would be directed towards the large gas fields expected to become depleted in a few years in the western part of Drava depression (HR.SU.13, HR.SU.14, HR.SU.15, HR.SU.16, HR.SU.19), although it should be noted that the largest emitter in that area is the Molve NGPP (HR.ES.5), whose emissions will decrease with the decline of gas production from the mentioned gas fields.

The second scenario for the Central cluster assumes that ,in a first phase, CO_2 coming from all sources except from NGPP Molve (HR.ES.5) would be injected in oil reservoirs for EOR operations (HR.SU.7, HR.SU.8, HR.SU.9, HR.SU.11, HR.SU.12) while CO_2 from NGPP Molve (HR.ES.5) would be injected into reservoirs of Šandrovac oil field (HR.SU.20) for EOR. Nowadays, there is an operational pipeline transport from Molve to western Sava, making the transport in opposite direction also viable.

In any case, CO_2 from sources within the Central Cluster is expected to be injected firstly in oil fields reservoirs as part of EOR operations and afterwards into depleted gas fields.

The two large emitters from the northern coastal part of Croatia, the Rijeka refinery (HR.ES.11) and the TE Plomin coal power plant (HR.ES.12), compose the Adriatic cluster. This cluster is quite distant from the storage sites, but it comprises the largest emitters in the region, with the Rijeka refinery being ready-to-transport CO_2. A consolidation hub at Rijeka should gather the CO_2 from the power plant and the refinery, before trunk transport along the natural gas magistral pipeline corridor to the west, i.e. to the storage sites in Central Croatia. In a first instance the hydrocarbon fields would be

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the target for CO_2 injection, but since this cluster emits more than 2Mt/y, it is likely that in the long run, storage has to be done in the DSA of Central Croatia or at the largest capacity hydrocarbon fields in eastern Croatia.

A scenario is also possible in which the CO_2 from this Adriatic cluster is connected via pipeline to the hubs in the Central cluster, either at the Zagreb hub or to Sisak hub and then trunk transported together to the injection sites in the hydrocarbon fields.

Finally, and although not included in STRATEGY CCUS, scenarios may exist that consider offshore storage in the Adriatic Sea.

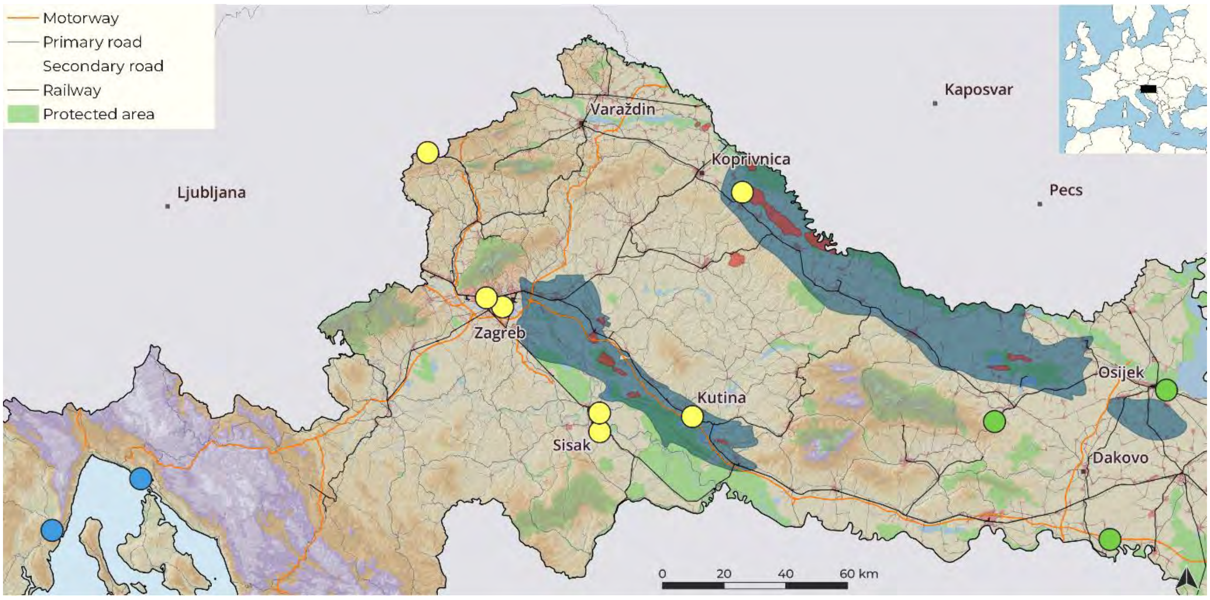

Figure 4-27 Clustering of CO_2 emitters and location of possible transport modes (roads, railways and ports). Light blue represents the Adriatic cluster, yellow the Central cluster and green the Eastern cluster.

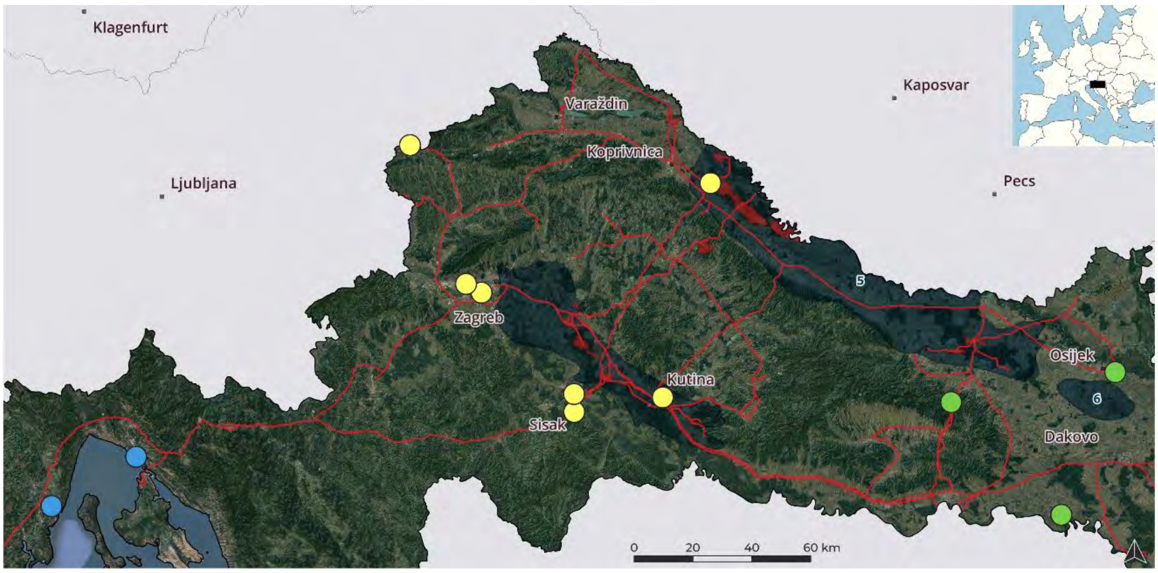

Figure 4-28 Clustering of CO_2 emitters and location of existing natural gas pipelines.

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4.4.4 CO_2 utilisation options

Enhanced Oil Recovery through CO_2 injection (CO_2-EOR) is the most relevant CO_2 utilisation activity ongoing and foreseen for Northern Croatia. CO_2 EOR projects are already cost-effectively storing CO_2 while gaining additional oil recovery at two fields ("Ivanić" and "Žutica"), and EOR projects are planned to be implemented at other oil fields as well. It is difficult to predict the planned implementation time, but for most of the reservoirs listed in Table 4-13, CO_2-EOR plans already exist.

Enhanced oil recovery may include different Water-Alternating-Gas (WAG) ratio options. Numerical simulation case study has been conducted for a number of scenarios with different WAG ratios and the most efficient scenario was selected for each possible field. The CO_2 utilisation estimates in table (Table 4-13) are based on the selected scenarios. Field oil production and both injected and produced quantities of CO_2 vary from year to year, so that minimum, maximum and average values are indicated in the table.

Note that the amount of CO_2 required on average varies from 0.28 Mt/y for the "Lipvoljani" field to 8.5 Mt/y for the "Beničanci" field. Any combination of two or three fields being exploited simultaneously would be enough to store all the CO_2 that is currently being produced in the Central and Eastern clusters.

On average, 40% to 60% of the injected CO_2 is produced back and emitted to the atmosphere, resulting in net reductions that range, on average, from 0.2 Mt/y for the smallest fields to 3.2 Mt/y for the largest fields. Still, the overall net reduction would be around 40%. In CO_2-EOR processes the re-emission of CO_2 can be prevented if the produced CO_2 is separated from the natural gas stream and then re-injected. That option would imply a higher CO_2 avoidance in the CO_2-EOR process, but would also require the smaller volumes of CO_2 to be captured at the existing sources specifically for the EOR process.

Table 4-13 Northern Croatia CO_2-EOR potential

Field	CO_2 used (t/year)			CO_2 emitted (t/year)			CO_2 produced (t/year)		
	min	max	average	min	max	average	min	max	average
Benicanci (HR.SU.017)	3 880 900	11 820 000	8 542 636	828 349	11 368 104	5 290 878	100 000	600 000	287 500
Ivanic (HR.SU.008)	3 743 000	8 214 900	5 890 300	14 757	7 814 860	3 500 604	100 000	300 000	138 046
Klostar (HR.SU.007)	2 639 800	5 713 000	3 957 909	1 046 044	5 489 628	2 518 876	57 944	155 231	91 361
Lipovljani (HR.SU.012)	151 690	433 400	275 800	229	197 249	80 386	155 230	155 232	155 231
Sandrovac (HR.SU.020)	2 206 400	3 940 000	2 979 625	605 200	2 735 073	1 274 061	100 000	117 481	102 390
Sturzec (HR.SU.OII)	4 373 400	7 683 000	5 892 091	910 862	7 403 227	3 593 427	100 000	400 000	250 000
Zutica (HR.SU.009)	1 223 370	2 797 400	1 849 584	28 585	2 256 557	769 124	100 000	300 000	181 250

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The Croatian national planning documents (Energy Development Strategy of the Republic of Croatia until 2030 with a view to 2050, Law on National Obligations to Reduce Emissions of Certain Air Pollutants in the Republic of Croatia, Law on Carbon Development Strategy of Croatia), also presents some statements that research on CO_2 uses in connection to hydrogen production, by 2030, will be encouraged. Still, there is no estimation of quantities or companies that will be included in that research effort.

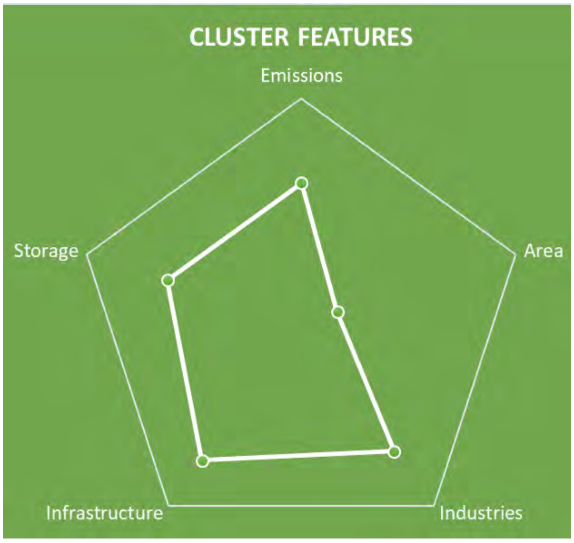
Hydrogen is currently produced in Croatia only at the INA's Rijeka refinery to satisfy the refinery's own needs. According to INA, the refinery has a higher production capacity and could sell hydrogen if there is a demand for it. Currently, in Croatia there is no demand for hydrogen as a fuel, but demand could exist by 2030. Nonetheless, it is doubtful that new facilities to produce hydrogen from natural gas reforming will be built by 2030, after which the decrease natural gas production will discourage even more building such facilities.

However, the goal is for hydrogen to contribute to decarbonization, so a hydrogen strategy could rely on green hydrogen (produced from renewable energy sources). In that respect, and as expected for other countries, there may be a role for CO_2 utilisation together with hydrogen to produce methane, methanol or other synthetic fuels.

4.4.5 Main features of technical potential for ICCUS development

Although there are important CO_2 sources in Northern Croatia, they are quite dispersed through the northern part of the country, without a clear locus that could be perceived as the spearhead of an ICCUS cluster. Perhaps the best locus is provided by the Rijeka refinery and the Plomin coal power plant, which although somewhat distant (30+ km) are the largest emitters in the region. However, they are also the sources farther away from the storage sites.

Half the sources in the area are power plants, for which decarbonisation alternatives lie in switch to biogas or biomass, which could create opportunities for BECCUS and negative emissions. There is an important fertilizer production facility and a gas processing facility, although the emission from the last are likely to decrease after 2030 as the producing hydrocarbon fields start depleting. Other industrial sectors are less important emitters, with one existing refinery due to be reconverted in bitumen producing facility, and relatively small cement and glass sectors (one facility each).



The existence of several hydrocarbon fields with potential for CO_2-EOR, which is already happening in two oil fields (CO_2 from Molve NGGP), and for long term CO_2 storage, is the strongest motivation for deploying CCUS in the promising region. The experience that the country already has in managing CO_2-EOR and a CO_2 pipeline from the Molve NGPP to the oil fields are also positive aspects.

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Table 4-14 Northern Croatia cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	Sources very dispersed across northern part of the country, from the borders with Serbia and Hungary, to the Adriatic Sea. Only in Zagreb and Sisak are there two sources less than 5 km apart.	-
	Emission volume distribution	Sources near the Adriatic (refinery at Rijeka and coal power plant at Plomin) are those with emission above 1 Mt/y, representing 40% of all emissions. All other sources with volumes between 0.1 Mt/y and 0.75 Mt/y.	~
	Emission volume profile	There is a growing trend in emission in 7 sources, falling trend in 3 sources, and stable in 2 sources.	+
	Emissions type and quality	Mostly combustion emissions, except for a biomass power plant and process emissions in a cement factory and a fertilizer production company.	+
AREA	Industrial area character	Most sources are power plants, but there are refineries (2), gas processing facility (1), fertilizer production (1) and glass (factory).	~
	Importance of industry	Industrial centres not highly developed. Industry seems low importance.	-
	Cluster recognition	Area not previously recognised as a cluster.	-
INDUSTRIES	Integration of industry	2 refineries operated by same company, and 5 power plants with same operator. Facilities do not share industrial complexes.	+
	Decarbonisation alternatives	Energy efficiency and fuel switch to biogas, hydrogen or biomass seem the options being considered.	~
	CCU	CO_2 -EOR ongoing in 2 oilfields and potential for several others. National plans mention hydrogen production and CO_2 uses.	+
	Motivation for decarbonisation	National strategies for climate mitigation	~
	Motivation for CCUS	Utilisation in EOR processes.	~
INFRASTRUCTURE	CO_2 collection options	Sources are connected to natural gas pipelines which could be used as the corridor for CO_2 pipelines. Small sources perhaps could use roadway transport.	+
	CO_2 consolidation options	Two sources in urban perimeter of Zagreb with more difficulties for consolidation. All other sources in rural areas or industrial complexes	+
	Existing CO_2 infrastructure	There is CO_2 capture facility at Molve gas processing plant. CO_2 is transported via pipeline to oilfields for CO_2 -EOR	+
	Infrastructure reuse options	Existing pipelines likely to continuing running natural gas, unlikely to be available for reuse.	-
STORAGE	Storage accessibility	Existing hydrocarbon fields relatively nearby most sources. Two large sources in Adriatic coast quite distant (150+ km from storage sites).	~
	Storage capacity	Adequate for the hydrocarbon fields, with backup capacity provided by DSA.	+
	Storage flexibility	Adequate, with several possible fields for CO_2 -EOR and with backup provided by DSA.	+
	Storage development integration	No organisation has put forward plans for developing storage.	-

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4.5 Paris basin – France

4.5.1 Emissions and industry sectors

The number of emissions sources inventoried in the Paris Basin promising region is quite high, with forty sources, compared to most other regions in STRATEGY CCUS, but the carbon intensity of each facility is relative low, so that the total emissions were only 4.9 Mt/y in 2018, the second smallest value in the STRATEGY CCUS regions, with an average emission of 0.12 Mt/y per source (Figure 4-29).

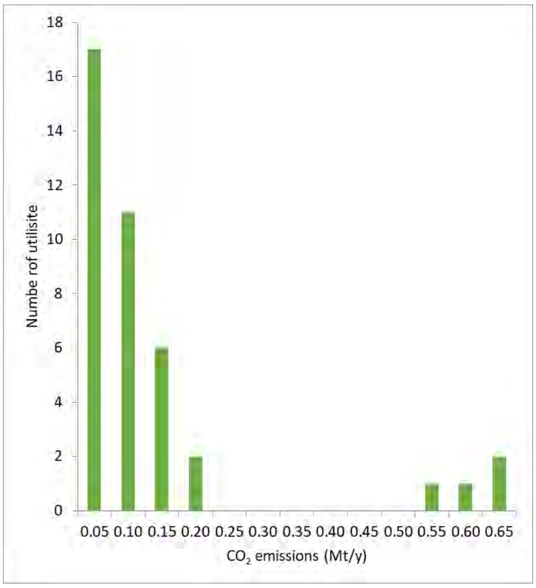

Figure 4-29 Frequency of sources per CO_2 emission in the Paris basin.

The largest source in the region, a Refinery at Grandpuits (FR1.ES.1), emits 0.65 Mt/y, and there are only four sources (the refinery, one chemical plant (FR1.ES.2) and two Energy-from-waste power plants, FR1.ES.3 and FR1.ES.4) emitting more than 0.5 Mt/y (Figure 4-30). All other sources emit less than 0.2 Mt/y and twenty-two sources emit less than 0.06 Mt/y (Table 4-15). Hence, although the number of existing sources is large, most of them are small-scale emitters and perhaps will not provide the impact in emissions reduction that is associated to an ICCUS cluster.

This asymmetry between number of sources and emissions is also reflected in the predominant industrial sectors (Figure 4-30). Energy-from-waste and CHP plants are the sectors with the highest number of facilities, fifteen and eleven, respectively. Energy-from-Waste has an average emission rate of 0.17 Mt/y/source, which together with the large number of facilities, makes the sector the largest emitter in the region (51% of the total emissions). The average CO_2 emissions in the power plants is only 0.04 Mt/y, making this a relatively irrelevant sector for capture purposes (the largest facility in the sector emits 0.084 Mt/y), but with potential for BECCS as many of these facilities are operating with biomass.

The opposite pattern is seen for the Refineries and Chemical sectors, each with only one facility, but being respectively the second and third most important emissions sectors, because the “Raffinerie de Grandpuits” (FR1.ES.1) and the “Borealis Grandpuits” chemical facility (FR1.ES.2) are the largest emitters in the area, totalling 1.27 Mt/y (Figure 4-30).

Thus, despite the large number of power plants, the most relevant sectors in the Paris Basin are the Energy-from-wasteand the chemical sector; the refinerie has high probability to shutdown in the coming years. In the Energy-from-Waste, the “IVRY PARIS XIII” (FR1.ES.3) and the “TSI” (FR1.ES.4) plants are responsible for 1.09 Mt/y, almost equivalent to the emissions of the other thirteen Energy-from-

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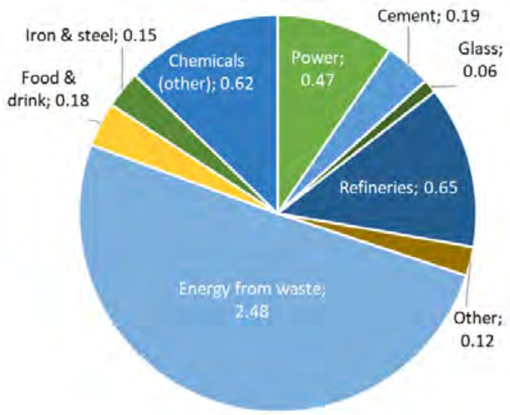
Waste plants. The cement sector, so relevant in other regions of STRATEGY CCUS, is relatively unimportant, since there is only one cement factory which emitted 0.19 Mt in 2018. However, in 2018, this factory produced at its half capacity due to maintenance works.

Average emissions per facility from the food & drink and the glass sectors are very small, and even in the usually carbon intensive iron & steel sector, the largest source (FR1.ES.18) emits 0.09 Mt/y (Figure 4-30).



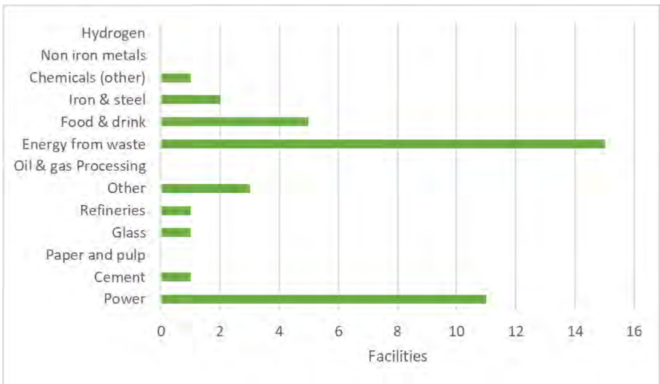
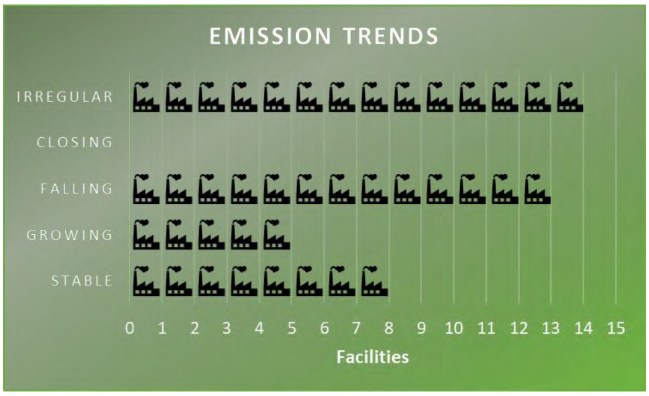


Figure 4-30 Emissions (in Mt/y) and facilities per sector in the Paris basin.

The sources are spread across the whole promising region, but only at Grandpuits, with the Refinery and chemical plant, and at western part of Paris, with the two largest Energy-from-Waste plants, there seems to exist the locus for onset of a ICCUS cluster based on large emitters aggregating other minor sources to build a common network.



Many of the sources in the area show a decreasing tendency in the emissions in recent years, with thirteen facilities having a "falling" trend, while only five other facilities have a "growing" trend in the emissions. All other sources present either a stabilisation or an irregular pattern in the emissions (Table 4-15).

Not surprisingly, given the number of Energy-from-waste plants, urban waste is the fuel used in most facilities, with fuel gas and natural gas being used at least in the two facilities at Grandpuits, , while biomass is indicated as the main fuel in the "Dalkia biomasse Orléans" (Table 4-15).

CO_2 emissions from non-fossil fuels combustion, is a very important proportion of the total emissions in the region, being estimated that up to 1.36 Mt/y, that is 28% of the total emissions, are related to biomass combustion, possibly raising the case for BECCS. This alternative may be

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particularly interesting for the two large Energy-from-waste plants, "IVRY PARIS XIII" and "TSI", where the CO_2 emissions from biomass are estimated respectively 0.34 Mt/y and 0.28 Mt/y.

The capture technology indicated as most likely to be applied at these facilities is Amine Based Solvents, except for the "Raffinerie de Grandpuits" and at "Alpa" Iron &steel plant, in which Oxycombustion is most likely, and the cement factory "Ciments Calcia usine de Gargenville" and the "BIO SPRINGER" food& drink where Calcium Looping may be more appropriate.

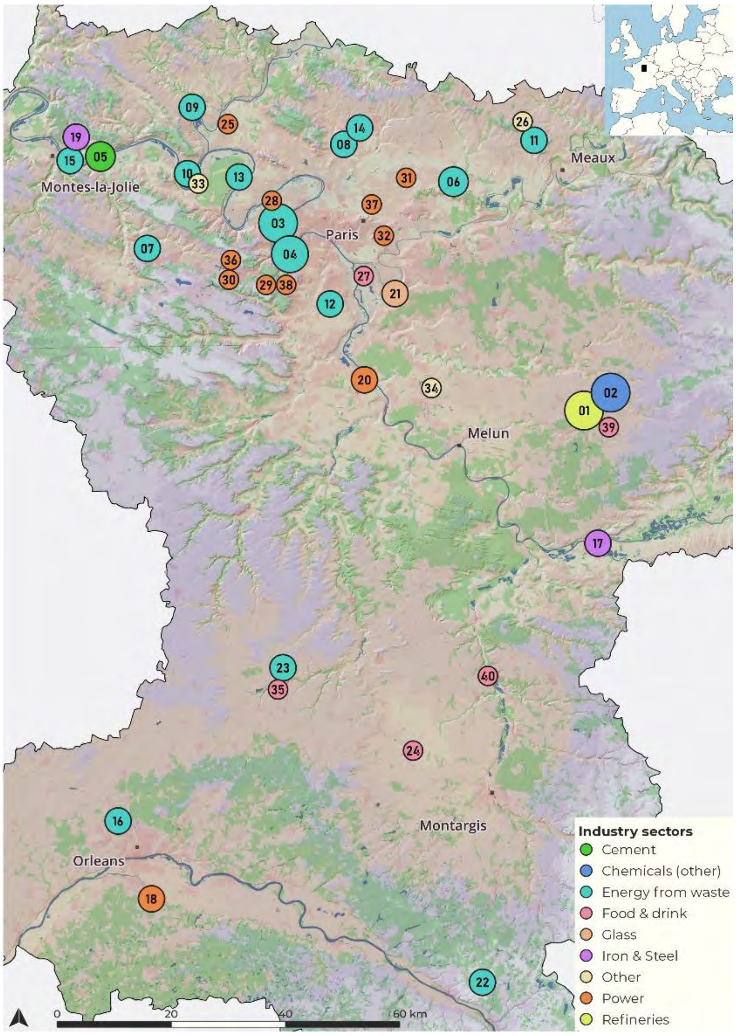

Figure 4-31 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-15. For detail see map in Appendix I.

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Table 4-15 Main features of CO_2 emitting facilities in the Paris basin

Emitter ID	Facility name	Sector	City	Emissions (tCO_2/y)	Emission trend	Main fuel
FR1.ES.1	Raffinerie De Grandpuits	Refineries	Mormant	648000	Falling	Gas fuel
FR1.ES.2	Borealis Grandpuits	Chemicals (other)	Mormant	624000	Irregular	Natural gas
FR1.ES.3	Ivry Paris Xiii	Energy from waste	Paris	592000	Stable	
FR1.ES.4	Tsi	Energy from waste	Issy-les-Moulineaux	504000	Growing	Waste
FR1.ES.5	Ciments Calcia Usine De Gargenville	Cement	Gargenville	187000	Falling	
FR1.ES.6	Veolia	Energy from waste	Claye-Souilly	157000	Falling	Waste
FR1.ES.7	Cvd Thiverval-Grignon	Energy from waste	Thiverval-Grignon	133000	Irregular	Waste
FR1.ES.8	Saren	Energy from waste	Sarcelles	132000	Growing	Waste
FR1.ES.9	Auror'Environnement	Energy from waste	Cergy	129000	Falling	Waste
FR1.ES.10	Azalys	Energy from waste	Carrières-sous-Poissy	126000	Falling	Waste
FR1.ES.11	Somoval	Energy from waste	Monthyon	112000	Stable	Waste
FR1.ES.12	Generis - Site De Rungis	Energy from waste	Rungis	101000	Falling	Waste
FR1.ES.13	SIAAP Site Seine Aval	Energy from waste	Maisons-Laffitte	99900	Falling	Waste
FR1.ES.14	Bouqueval Energie	Energy from waste	Le Plessis-Gassot	98700	Falling	Waste
FR1.ES.15	Sarp Industries	Energy from waste	Limay	96400	Irregular	Waste
FR1.ES.16	Orvade	Energy from waste	Saran	94800	Irregular	Waste
FR1.ES.17	Sam Montereau	Iron & Steel	Montereau-Fault-Yonne	90900	Irregular	
FR1.ES.18	Dalkia Biomasse Orléans	Power	Orléans	84000	Falling	Biomass
FR1.ES.19	Alpa	Iron & Steel	Porcheville	57900	Growing	
FR1.ES.20	Grand Paris Sud Energie Positive	Power	Evry	55500	Growing	
FR1.ES.21	Sgd Usine De Sucy En Brie	Glass	Sucy-en-Brie	55000	Stable	
FR1.ES.22	Uiom Gien-Chateauneuf	Energy from waste	Gien	54000	Falling	Waste
FR1.ES.23	Cve Pithiviers	Energy from waste	Pithiviers	50100	Stable	Waste
FR1.ES.24	Cristal Union Etablissement De Corbeilles	Food & drink	Corbeilles	49700	Irregular	Natural gas
FR1.ES.25	Cyel	Power	Saint-Ouen-l'Aumône	48400	Irregular	
FR1.ES.26	Knauf Plâtres	Other	Saint-Soupplets	47800	Stable	
FR1.ES.27	Bio Springer	Food & drink	Maisons-Alfort	44100	Stable	
FR1.ES.28	Enertherm Noël Pons	Power	Nanterre	41800	Irregular	
FR1.ES.29	Velidis Chaufferie Vélizy V3	Power	Vélizy-Villacoublay	39500	Falling	
FR1.ES.30	Verseo	Power	Versailles	37000	Irregular	
FR1.ES.31	Chaufferie Zup De Sevran	Power	Sevran	36100	Irregular	
FR1.ES.32	Chaufferie Zup De Fontenay	Power	Fontenay-sous-Bois	35400	Falling	
FR1.ES.33	Peugeot Citroën Poissy Snc	Other	Poissy	34500	Falling	
FR1.ES.34	Safran Aircraft Engines	Other	Moissy-Cramayel	34400	Irregular	
FR1.ES.35	Etablissement De Pithiviers Le Vieil	Food & drink	Pithiviers-le-Vieil	32900	Irregular	
FR1.ES.36	Chaufferie De Parly 2	Power	Le Chesnay	32400	Stable	
FR1.ES.37	Semeco (Et Idex Energies)	Power	Bobigny	30700	Stable	
FR1.ES.38	Engie Chaufferie De Meudon	Power	Meudon	27500	Growing	
FR1.ES.39	Lesaffre Freres	Food & drink	Nangis	27200	Irregular	
FR1.ES.40	Ouvre Fils Sucrerie Et Distillerie	Food & drink	Souppes-sur-Loing	23000	Irregular	

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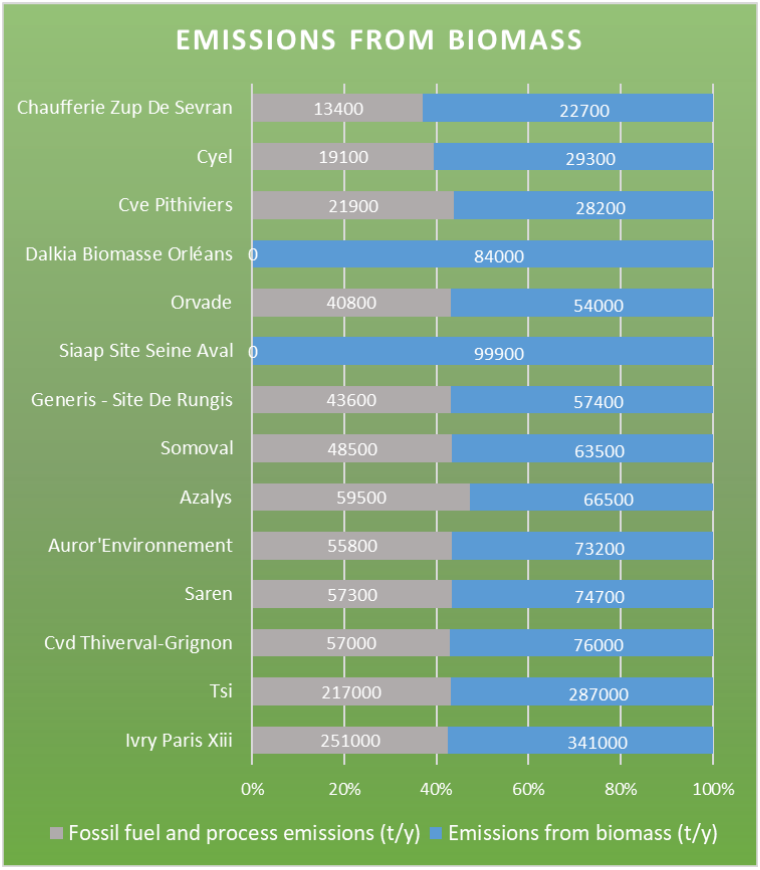
4.5.2 CO_2 Storage possibilities

There are two types of geological storage units in the Paris Basin, Deep Saline Aquifers (DSA) with a total storage capacity of 222 Mt, and Depleted Hydrocarbon Fields (DHF), with half the storage capacity, 111 Mt (Table 4-16). The level of confidence on data and knowledge about the geological conditions for both storage types is very different, with the DHF being prospect resources, with highly detailed information about the storage sites, while the DSA are Tier 2 (Daughter units) resources.

Given that the current emissions in the Paris Basin amount to 4.9 Mt/y, the DHFs are probably adequate to store CO_2 for several decades, particularly if complemented with storage capacity in the DSAs. The DHFs, being prospects, will suffer some reduction in the storage capacity estimates, but surely a higher reduction is expected for the Tier 2 aquifers. Furthermore, the sealing capacity of the hydrocarbon fields is proven. In the short term, DHF are likely to be the preferential targets for CO_2 storage in the Paris Basin, while waiting for proven capacities in DSA prospects.

Yet, the storage capacity in DHF is unevenly distributed by thirty-three prospects, with a single structure "Coulommes" (FR1.SU.33) being responsible for 53 Mt, nearly half of the storage capacity provided by DHFs. Another three prospects ("Donnemarie" (FR1.SU.8), "Chailly" (FR1.SU.28) and "Villemer" (FR1.SU.35)) have a storage capacity ranging from 11.6 Mt to 15.3 Mt (Figure 4-33). Hence, four prospects account for 83% of the DHF storage capacity and those are the prospects worth considering for CO_2 storage in the Paris Basin. All other prospects have a storage capacity below 3.5 Mt and can probably be discarded for large-scale storage, but they may be suitable for storing CO_2 from individual small-scale sources.



The four largest DHFs prospects are located to the East and Southeast of Paris, in the Seine-et-Marne Department, 40 km to 50 km from the city, but closer to some of the most important sources in the region, namely those at Grandpuits, which are less than 20 km away from the "Donnemarie" prospect and 30 km from the larger prospect, "Coulommes" (Figure 4-32).

Other important sources are relatively close to those four DHF prospects. The "Sam Montereau" Iron & Steel plant, FR1.ES.17, (0.09

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$MtCO_2/y$) at Montereau-Fault-Yonne is roughly equidistant (around 20 km) from the “Donnemarie”, “Chailly” and “Villemer” prospects, while the “Somoval”, FR1.ES.11, (0.112 Mt/y) and the “Veolia”, FR1.ES.6, (0.57 Mt/y) Energy-from-Waste plants are at 15 km and 20 km from the “Coulommes” prospects. It is reasonable to consider that there is a good spatial match between the DHF prospects and the main emitting facilities East from Paris.

The expectations for storage in DSAs are somewhat different due to the uncertainty about the storage capacity. Five storage units in DSAs were defined in the Middle - Upper Triassic (Keuper) Sandstones and conglomerates and classified as Tier 2, with storage capacities ranging from 9.8 Mt to 81.5 Mt (Figure 4-33).

The Triassic formations in the Paris Basin extend for a very large area, but the five storage units in saline aquifers have been defined in two areas NE and South from Paris (Figure 4-32). The highest capacity storage unit “(Chailly-Chaunoy” formation (FR1.SU.5) – 81.,5 Mt) is located NE from Paris, mostly in the Seine-et-Marne Department, but extending to the neighbouring Oise and Aisne departments. It encompasses the area where one of the most relevant DHF fields (“Coulommes”) exists, and thus it is probably a suitable storage opportunity for the same sources.

The other four storage units, with a total storage capacity of 140.7 Mt, occur south from Paris, still within the southern part of the Seine-et-Marne Department, but extending to the Essonne, Eure-et-Loire and Loiret Departments (Figure 4-32). The northern part of the area includes the location of some DHF, but it provides a storage opportunity for sources located in the surroundings of Orleans, notably the “Orvade” Energy-from-Waste plant (0.095 Mt/y) and the “Dalkia Biomasse Orléans“ plant (0.084 Mt/y). The four sources around Nemours, Corbeilles and Pithiviers (one Energy-from-Waste plant and three sugar refining facilities) are also well located for storage in these storage units, but the emissions are very small.

The deep saline aquifer may present better storage opportunities for those source located west from Paris, namely the Energy-to-Waste Plants “Ivry Paris XIII”, “TSI”, “Auror'environnement“, “Azalys” and “CVD Thiverval-Grignon “ and the cement factory “Ciments Calcia usine de Gargenville“, all of which are located west from Paris and thus closer to the DSAs than to the depleted hydrocarbon fields.

The DSA structures are assessed at Tier 2 and will require further works in terms of characterization to prove their usefulness for CO_2 storage while advancing in Tier, with consequential decreases in storage capacity. Still, given the relatively low level of emissions in the Paris Basin and the more than 200 Mt Tier 2 capacity, it is likely that the DSA can add flexibility to the storage capacity in the DHFs.

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Table 4-16 Main features of potential storage units in the Paris basin

Storage Unit	Storage type	Storage Unit	Daughter unit	Prospect	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)
FR1.SU.1	DSA	Trias	Chailan	Keuper Sud	shale and clastic sandstone	Onshore	-2000	300	29.55
FR1.SU.2	DSA	Trias	Chailly-Chaunoy	Keuper Sud	conglomerat and clastic sandstone	Onshore	-2250	300	9.85
FR1.SU.3	DSA	Trias	Grès Intermediaire	Keuper Sud	conglomerate and clastic sandstone	Onshore		300	32.36
FR1.SU.4	DSA	Trias	Donnemarie	Keuper Sud	conglomerate and clastic sandstone	Onshore	-2500	300	68.94
FR1.SU.5	DSA	Trias	Chailly-Chaunoy formation	Keuper Nord	interbedded sandstone / shales	Onshore	-2276	271	81.50
FR1.SU.6	DHF	Trias	Chaunoy / Donnemarie sandstones	Fay-Les-Nemours		Onshore			
FR1.SU.7	DHF	Trias	Chaunoy / Donnemarie sandstones	Champrose		Onshore			
FR1.SU.8	DHF	Trias	Chaunoy / Donnemarie sandstones	Donnemarie		Onshore	2538	37	11.60
FR1.SU.9	DHF	Trias	Chaunoy / Donnemarie sandstones	Sivry		Onshore	1790	25	0.00
FR1.SU.10	DHF	Trias	Chaunoy / Donnemarie sandstones	Maincy		Onshore	1840	25	0.00
FR1.SU.11	DHF	Trias	Chaunoy / Donnemarie sandstones	Vert-Le-Grand	Chonoy SS	Onshore	1875	25	3.39
FR1.SU.12	DHF	Trias	Chaunoy / Donnemarie sandstones	Pezarches	Chonoy SS	Onshore	2440	25	0.35
FR1.SU.13	DHF	Trias	Chaunoy / Donnemarie sandstones	Nesles	Chonoy SS	Onshore	2375	25	0.00
FR1.SU.14	DHF	Trias	Chaunoy / Donnemarie sandstones	Malnoue	Limestone	Onshore	1975	25	0.32
FR1.SU.15	DHF	Trias	Chaunoy / Donnemarie sandstones	Ile-du-Gord	Chonoy SS	Onshore	2203	25	0.00
FR1.SU.16	DHF	Trias	Chaunoy / Donnemarie sandstones	Charmottes	Donnemarie SS	Onshore	2560	25	1.71
FR1.SU.17	DHF	Trias	Chaunoy / Donnemarie sandstones	Champotran	Chonoy SS	Onshore	2495	25	3.15
FR1.SU.18	DHF	Trias	Chaunoy / Donnemarie sandstones	Chailly		Onshore	2136	25	2.10
FR1.SU.19	DHF	Trias	Chaunoy / Donnemarie sandstones	Brie	Chonoy SS	Onshore	2150	25	0.00
FR1.SU.20	DHF	Trias	Chaunoy / Donnemarie sandstones	Bremonderie	Donnemarie SS	Onshore	2620	25	0.12
FR1.SU.21	DHF	Trias	Chaunoy / Donnemarie sandstones	La Vignotte	Marine	Onshore	2444	25	0.27
FR1.SU.22	DHF	Dogger	Comblanchian / Dalle Nacrée	Bechevret		Onshore			

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			limestones						
FR1.SU.23	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Villemer		Onshore	2045	25	0.64
FR1.SU.24	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Valence-en-Brie		Onshore	1629	25	0.32
FR1.SU.25	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Malnoue		Onshore		25	
FR1.SU.26	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Malnoue	Chonoy SS	Onshore	2680	25	1.54
FR1.SU.27	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Charmottes	Limestone	Onshore	1780	25	0.47
FR1.SU.28	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Chailly		Onshore	1582	25	12.10
FR1.SU.29	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Vulaines	Limestone	Onshore	1835	25	0.00
FR1.SU.30	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Vert-le-petit	Limestone	Onshore	1510	25	0.55
FR1.SU.31	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Coulommes	limestone	Onshore	1677	25	53.10
FR1.SU.32	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Itteville	Limestone	Onshore	1533	25	3.04
FR1.SU.33	DHF	Dogger	Comblanchian / Dalle Nacrée limestones	Coulommes	Limestone	Onshore	1850	25	0.00
FR1.SU.34	DHF	Trias	Hugleville limestones	L'Orme	Dolomitic	Onshore	1564	25	0.13
FR1.SU.35	DHF	Trias	Rhaetian sandstones	Villemer		Onshore	1435	25	15.30
FR1.SU.36	DHF	Trias	Rhaetian sandstones	La Croix Blanche	Continental	Onshore	1519	25	0.40
FR1.SU.37	DHF	Trias	Rhaetian sandstones	Marolles-en-Hurepoix	Continental	Onshore	1875	25	0.34
FR1.SU.38	DHF	Trias	Rhaetian sandstones	La Vignotte	Marine	Onshore	2444	25	0.27

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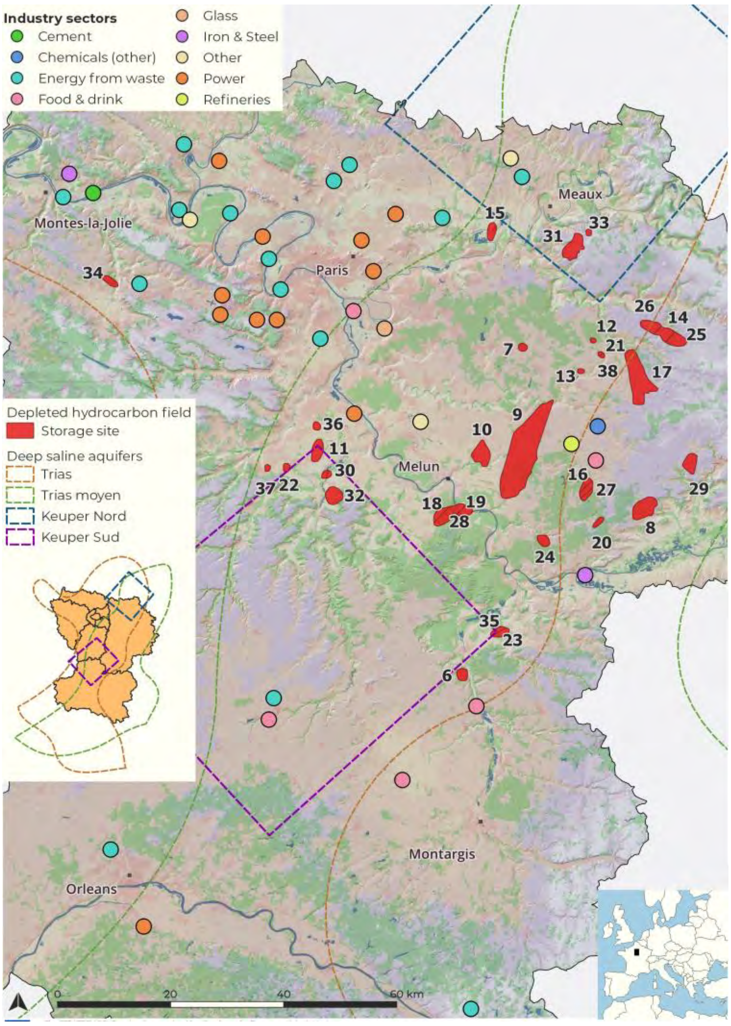

Figure 4-32 Potential storage units in the Paris basin. Numbers represent the *unit ID* in Table 4-15. For detail see map in Appendix I.

4.5.3 Spatial conditions for cluster and network development

The sources distribution in the Paris Basin point towards several potential clusters, considering the distance between sources and their proximity to the storage sites.

Two main clusters could be formed around the four larger emitters (Figure 4-36). The Refinery and the chemical plant at Grandpuits are aggregating elements of a group to which the "Sam Montereau" Iron & Steel mill (FR1.ES.17) at Montereau Fault-Yonne could be added. This group of sources, hereby designated by "Mormant" emitted 1.36 Mt in 2018, i.e. 28% of the total emissions in the Paris Basin. Other sources (e.g. FR1.ES.39) in the area have nearly negligible emissions.

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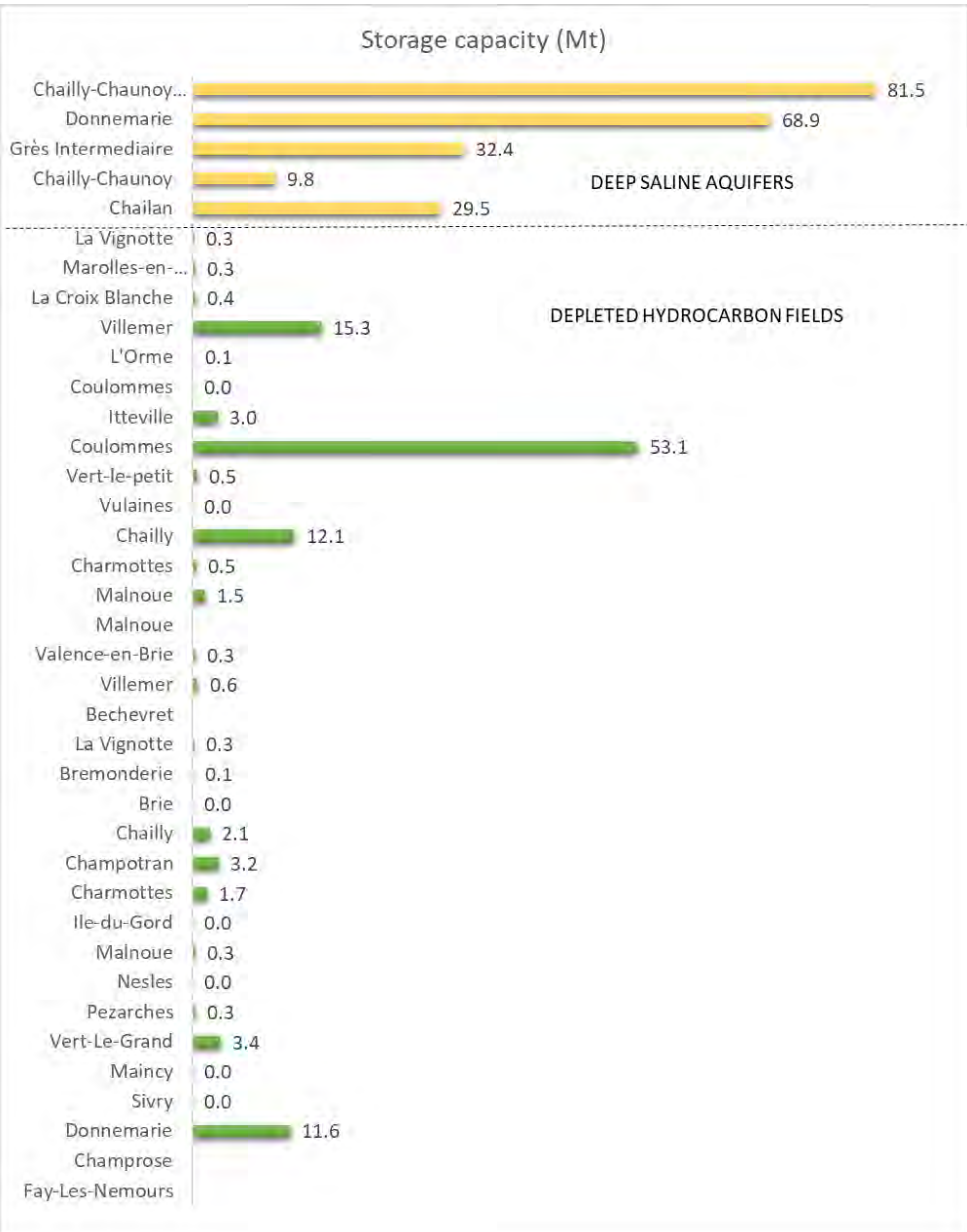

Figure 4-33 Distribution of storage capacity per storage unit. Yellow – Deep Saline Aquifers, Green – Depleted Hydrocarbon Fields.

These three sources are in industrial complexes in otherwise rural areas, without anticipated problems for space to build capture facilities or specific transport infrastructures. The industrial complex at Grandpuits is linked to a natural gas pipeline infrastructure which, however, does not seem to connect to the Iron & Steel mill.

The two sources at Grandpuits, being at the same industrial complex and emitting together 1.28 Mt/y, can benefit from pipeline transport, given the volumes involved, but the Iron&steel mill emits less than 0.1 Mt/y and transport in liquid form either by train or by road could be an interesting option, since the source is relatively isolated to consider linking to a purposely built pipeline.

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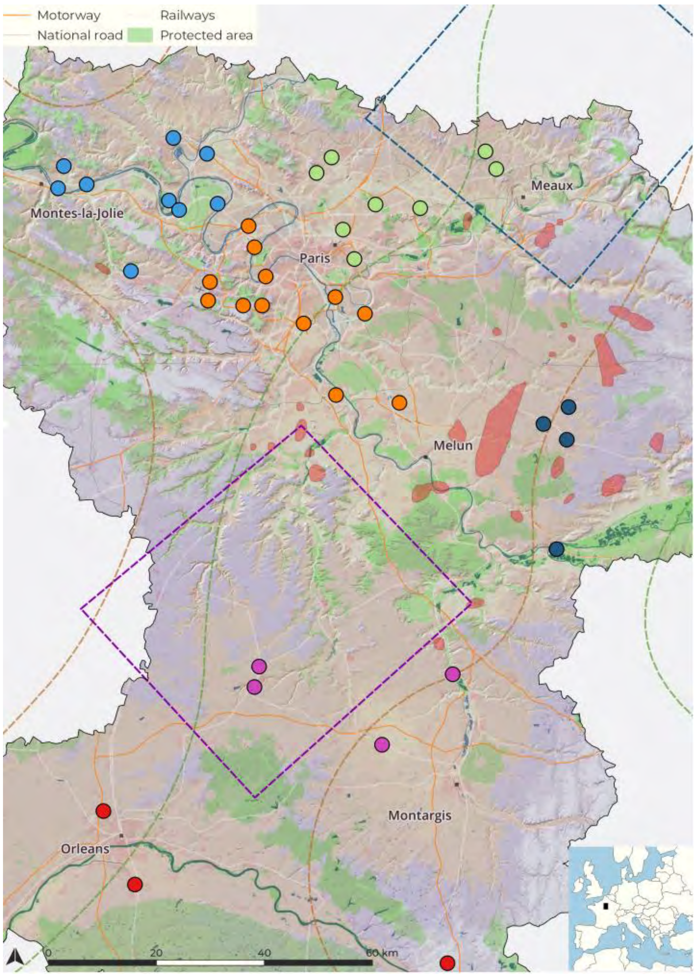

Figure 4-34 Clustering of CO_2 emitters and location of possible transport modes (roads, railways and ports). Light blue represents the Calcia cluster, dark blue the Mormant cluster, light green the Saint-Denis cluster, red the Orléans cluster.

The target for storage of the emissions from these sources is the "Donnemarie" (FR1.SU.8) DHF prospect, with a capacity of 11.6 Mt, and located 14.5 km away from the Grandpuits sources and the 16 km from the Iron & Steel mill. Since the available storage capacity is not very high, some flexibility would be required to store also in the "Chailly" (FR1.SU.18) and "Villemer" (FR1.SU.23) prospects, less than 40 km east and south from the sources and with another 27.4 Mt storage capacity.

A second group of sources is formed at "Ivry Paris 13", in the western part of Paris, including three large Energy-from-waste plants: "Ivry Paris XIII" (FR1.ES.3), "TFI" (FR1.ES.4), and "Generis - Site de Rungis" (FR1.ES.12). These three plants are responsible for 1.2 Mt/y, 24% of the regional emissions. Around the "Ivry Paris 13" cluster there are six power plants, one glass factory and one spacecraft engine factory, all with emissions lower than 0.06 Mt/y and several of them showing a decreasing trend in emissions.

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Figure 4-35 Left: Sources at Grandpuits. Right: Mormant cluster, also showing the nearest depleted hydrocarbon fields and natural gas pipeline network.

Unlike the sources at Grandpuits, the Energy-from-Waste plants at the “Ivry Paris 13” cluster are located in an urban setting, and at least for the “IVRY PARIS XIII” and “TFI” power plants, it is not obvious that enough space is available to build large scale capture facilities.

This urban setting also poses challenges to CO_2 collection to a hub. Obviously, the sources are accessible by road, crossing extensive areas of urban streets and roads, but the emissions at “Ivry Paris XIII”, “TFI” are too high and require a different transport mean. The existing natural gas pipeline network connects to these two sources, but is 6 km distant from the “Generis - Site de Rungis” plant. Finally, as a transport option, “Ivry Paris XIII” and “TFI” power plants are just a few hundreds of meters away from the Seine river, while the “Generis - Site de Rungis” is 4.5 km away from the river.

Thus, collection and transport are more challenging for this group of sources. In any case the “Generis - Site de Rungis” plant is distant from the other two and emits a lot less (0.1 Mt/y) so that transport in liquid form, by rail or by road needs to be considered. The other two sources are distant 5 km from each other, near the margins of the Seine, emit between 0.5 Mt/y to 0.6 Mt/y and are connected by an existing pipeline. Presumably this will not be available for CO_2transport, but perhaps the same corridor can be used for a new pipeline for CO_2, consolidating the CO_2 from these two sources and transporting it to the depleted hydrocarbon field at “Coulommes“, northeast from

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Paris. This DHF has an estimated storage capacity of 53.1 Mt, more than enough to store decades of emissions from the sources at the "Ivry Paris 13" group, and the natural gas pipeline runs nearby.

Other possible storage location for these sources would be the deep saline aquifers at Keuper Sud which may have more than enough capacity, or the DHFs at Chailly (12.1 Mt) and at Villemer (15.3 Mt), upstream from the sources along the river Seine.

A third group of sources is found even further west from Paris, forming the Calcia cluster, again dominated by five Energy-from-Waste plants, the Calcia cement plant (FR1.ES.5) and the ALPA Iron & steel plant (FR1.ES.19). These seven sources total 0.83 Mt/y, with the largest emitter being the cement plant with 0.19 Mt/y (at its half capacity). Other sources exist in the area, but even with smaller emissions.

Figure 4-36 Sources in the "Ivry Paris 13 cluster", set in an urban environment.

The sources in the Calcia cluster are located along the margins of the Seine (except for the "CVD Thiverval-Grignon" (FR1.ES.7) and "Auror'environnement" (FR1.ES.9) energy-from waste plants) 10km to 36 km downstream from the "Ivry Paris 13" cluster sources, but for the most part are in a rural environment. There should not be difficulties in finding space for building capture infrastructures and transport probably faces less challenges than the "Ivry Paris 13" cluster. Still the "SIAAP Site Seine Aval" (FR1.ES.13) is in the urban area of Maisons-Laffitte.

The range of emissions in these sources varies from 0.058 Mt/y at the "Alpa" iron & steel mill to 0.19 Mt/y at the Calcia cement plant. These are small volumes, and thus individualised liquified transport by road or by rail (some sources, for instance "SARP Industries" power plant and "Alpa" iron & and steel have dedicated rail terminals in their facilities), or even by waterway along the Seine (the Calcia cement plant has a pier) may be a possibility

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Otherwise, pipeline transport could be considered through a new collection infrastructure. A hub, in the outskirts of Maisons-Laffitte or Pontoise, could provide the consolidation before trunk transport to the same storage locations as the “Ivry Paris 13” cluster.

North from Paris, the cluster of Saint-Denis includes four Waste-to-Energy power plants, spread along 32 km, with emissions ranging from 0.1 Mt/y to 0.16Mt/y, and totalling 0.5Mt/y. Set in rural areas, space for building capture facilities may not be a big problem and transport also should face less constraints than other clusters around Paris. In fact, building a pipeline along the same corridor of the pipeline that connects them and set a consolidation hub around the towns of Monthyon or Saint-Soupplets, already in the area of the Keuper Nord Deep Saline aquifers, is possibly a valid alternative.

Finally, at Orleans, the “ORVADE” Energy-from-waste” plant (FR1.ES.16) emits 0.095 Mt/y and the “Dalkia Biomasse Orléans” power plant (FR1.ES.18) emits 0.084. The sources are 14 km distant, but CO_2 could be collected by road transport to a common hub before being transported to an injection point at the DSA Keuper Sud, where storage capacity is more than enough for the actual needs.

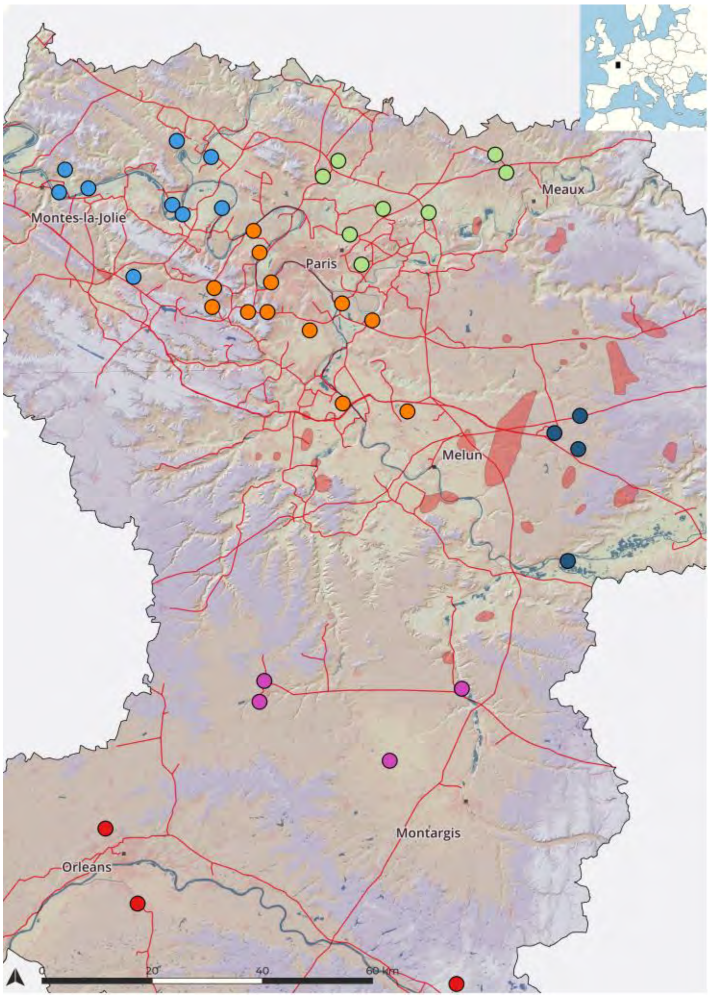

Figure 4-37 Clustering of CO_2 sources and existing natural gas pipelines.

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There are several other smaller sources spread around the promising region, some of which could be integrated in the above-mentioned groups. Those smaller sources are mostly heat generating plants or food & drink facilities, with emissions too small to be as first-starters of an ICCUS cluster.

4.5.4 CO_2 utilisation options

The French roadmap for climate change mitigation is presented in the National Low-Carbon Strategy (SNBC) issued in 2015 and revised in 2019 (SNBC2). SNBC2 mentions Carbon Capture Use and Storage and there is an appendix dedicated to CCUS. However, this remains at a very general level, especially concerning CO_2 uses. Concrete examples about carbon use are: substitution of fossil energy/synthetic fuel/methanation (combining CO_2 and H_2) and long-life products such as "building materials/manufactured products".

In SNBC2, uses of captured CO_2 are considered as a priority research area at national level. The SNBC2 encourages the development and implementation of pilot, and possibly commercial, CCS and CCU projects.

4.5.4.1 On-going CCU projects

There is a pre-feasibility study being done in the ongoing CO_2SERRE research project, focusing in the Orléans area, and funded by the Centre-Val de Loire Region. CO_2SERRE concerns the capture of biogenic CO_2 from a biomass-energy plant and a sugar plant, for utilisation in greenhouse crops and storage in DSA Keuper Sud.

Utilisation of CO_2 as a working fluid in Enhanced Geothermal Systems is being studied in the Centre-Val de Loire Region and in the Paris area (GEOCO_2 and PILOTE CO_2-DISSOLVED research projects). This technology couples CCS with geothermal energy recovery by injecting dissolved CO_2 in a geothermal doublet loop.

In the northern part of the Paris Basin, but very distant from the STRATEGY CCUS region, there is an ongoing H2020 research & innovation project, the 3D project, aiming at demonstrating the DMXTM CO_2 Capture technology in ArcelorMittal's Dunkirk steel mill on an industrial pilot plant (0.5 tCO_2/hr), bringing TRL from 4 to 7. Captured CO_2 is planned to be send to North Sea infrastructures.

4.5.4.2 Carbon use perspective in Paris Basin

Greenhouse crops

The Loire valley (around Orléans) comprises more than 40 ha of greenhouses (first estimate). Half of the operators already inject CO_2 in their greenhouses to boost plants growth. CO_2 injection is performed some months per year (January-April in the Loire valley). A first rough estimate would give a potential of CO_2 needs in the Loire valley greenhouses around 12kt/y.

Fertilizer industry

The region around Paris / Ile de France is an agricultural zone and the Fertilizer Industry in the Region is one of the most important emitters.

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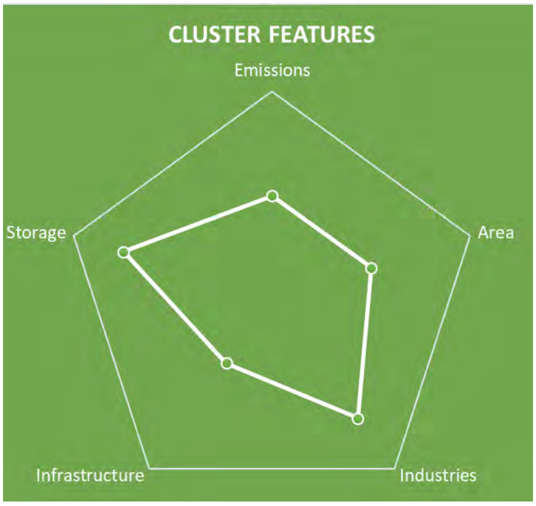
4.5.5 Main features of technical potential for ICCUS development

There are two main factors that favour the implementation of an ICCUS cluster in the Paris Basin promising region, namely the potential for BECCS and the available storage capacity in depleted hydrocarbon fields and deep saline aquifers.

The region has some manufacturing industry, but emissions are amongst the lowest in the STRATEGY CCUS promising regions. The considerable number of Energy-from waste plants and specially "Ivry Paris XII" and "TFI" plants provide a very favourable opportunity for achieving negative emissions with BECCS, a solution that could be extended to other Energy-from-waste plants. Other sources with potential for implementing CO_2 capture are the refinery and chemical plant at Grandpuits, the two largest emitters in the area and that are integrated in the same industrial complex. These two sources could become the aggregators for an ICCUS cluster east from Paris.

This potential for CO_2 capture is easily met by the existing CO_2 storage capacity, especially at four depleted hydrocarbon fields, that if managed with flexibility can store several decades of the CO_2 that can be captured in the region. DHFs should be the primary targets for CO_2 storage, given the accumulated knowledge about the geological conditions and the proven containment capacity. Furthermore, deep saline aquifers in the Keuper formations can provide additional storage capacity.

Design of the collection and transport network needs to take into account that the volume of CO_2 produced in each sources is often relatively small, and that transport in liquid phase using roads, railways or even barges along the Seine, can be a feasible possibility for some sources.



There is some CO_2 utilisation already ongoing in greenhouses, and further projects are being studied, but with a very limited utilisation capacity, of only 12 kt/y. Enhanced geothermal systems can also resort to CO_2 as a working fluid, but the volumes expected to be needed are also very small. More intensive uses would result from the conversion to synthetic fuels / methanation or for building materials, as mentioned in the national roadmap. However, except for the medium sized Total's refinery at Grandpuits and the Calcia's cement factory at Gargenville, there does not seem to be many facilities available for production of synthetic fuels or building materials in the area.

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Table 4-17 Paris Basin cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,−
EMISSIONS	Emission location distribution	Most sources spread along the surroundings (or even with the limits) of the city of Paris, but some sources in the Seine-et-Marne Department and in Orleans.	-
	Emission volume distribution	Two main loci for large emitters: Grandpuits (Mormant) with a refinery and a chemical plant, and in west Paris (Ivry Paris 13) with two large Waste-to-Energy power plants. All other sources much smaller.	+
	Emission volume profile	Several sources with falling trend in emissions, particularly in the Waste-to-Energy plants.	-
	Emissions type and quality	A high percentage of emissions from waste and biomass, but industrial processes in a cement factory and two iron & steel mills also relevant. Good potential for BECCS.	+
AREA	Industrial area character	Majority of emissions coming from Energy-from-Waste plants. One small refinery, a cement factory and two small iron & steel mills.	~
	Importance of industry	Some manufacturing industry, but not a highly industrialised region.	-
	Cluster recognition	Included in the first assessments of GEOCAPACITY, GESTCO and in ongoing CO_2SERRE projects	+
INDUSTRIES	Integration of industry	Refinery and chemical industry in Grandpuits integrated in the same industrial perimeter. All other sources without an obvious integration.	~
	Decarbonisation alternatives	Waste and biomass already used in many facilities. Not indicated, but conversion to hydrogen could be possible for the refinery and iron & steel.	+
	CCU	Ongoing utilisation in greenhouses. The industry in the region may not be focused on mineral carbonation or methanation/synfuel production	~
	Motivation for decarbonisation	National strategies for climate mitigation	~
	Motivation for CCS	Negative emissions could be achieved in Energy-from-waste plants. Increased utilisation of CO_2 in greenhouses and EGS	+
INFRASTRUCTURE	CO_2 collection options	Low volumes of emissions in many sources can lead to collection via rail (several sources with dedicated terminals) or road. Larger sources in Grandpuits and Ivry Paris 13 could use purposely built pipeline. Seine river could be used for collection from sources river side sources.	+
	CO_2 consolidation options	Sources in Ivry Paris 13 could face difficulties for consolidation due to highly urbanised area. All other sources with plenty of space available for CO_2 consolidation.	~
	Existing CO_2 infrastructure	No existing infrastructure.	−
	Infrastructure reuse options	Existing pipelines likely to continuing running natural gas, unlikely to be available for reuse.	-
STORAGE	Storage accessibility	Storage units at reasonable distance, usually less than 40 km from sources.	+
	Storage capacity	Enough storage capacity for the needs, with DHF providing good opportunities. Also, DSA at tier 2 assessment with enough storage capacity.	+
	Storage flexibility	Four DHF and five DSA storage units should provide enough flexibility.	+
	Storage development integration	No organisation has put forward plans for developing storage-	-

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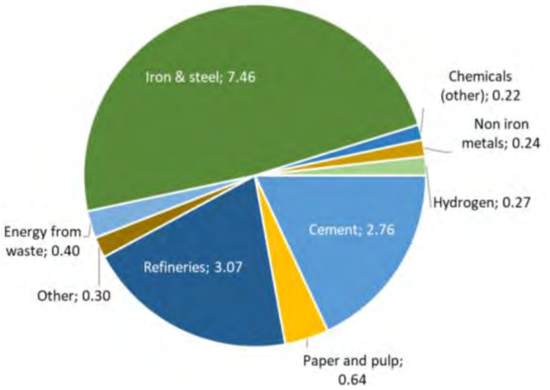
4.6 Rhone Valley – France

4.6.1 Emissions and industry sectors

The Rhone Valley promising region has the highest number of CO_2 sources in STRATEGY CCUS. Forty-eight emitting facilities were mapped, with a minimum CO_2 emission of 25.2 kt/y and a maximum of 7.46 Mt/y in 2018. As a whole, in that year, the 48 sources emitted 18.61 Mt. However, for the purposes of defining ICCUS only eighteen sources were retained, those located nearest the valley of the Rhone and with emissions big enough to have an impact to climate change mitigation (Table 4-18).

These eighteen facilities were responsible for 15.37 Mt CO_2 in 2018, i.e covering 83% of the total emissions in the Rhone Valley. The cement sector has the largest number of operational facilities in the region (6) and emitted 2.76 Mt/y as some of the plants are relatively small scale. On the opposite, a single iron&steel mill "ArcelorMittal FOS" (FR2.ES.1) at Fos-sur-Mer is responsible for 7.46 Mt/y, by far the largest emitter in the region (Figure 4-38).



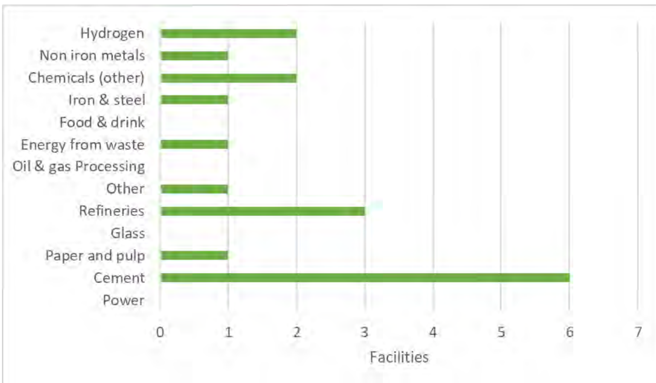
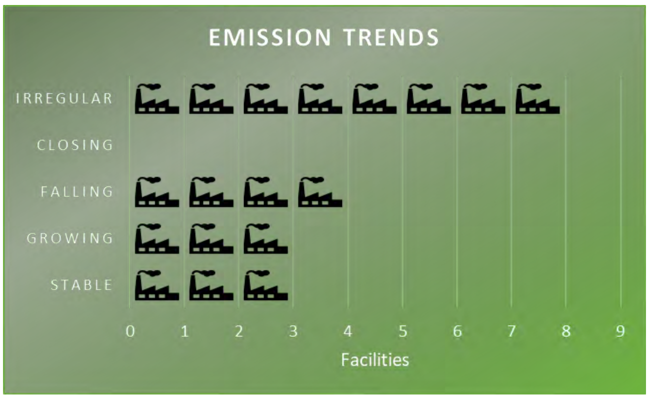


Figure 4-38 Emissions (in Mt/y) and facilities per sector in the Rhone Valley.

A high carbon intensity is found also in the three refineries, "Raffinerie de Feyzin" (FR2.ES.2) at Lyon, "Raffinerie ESSO" (FR2.ES.10) at Fos-sur-Mer and "Petroineos Manufacturing France SAS"(FR2.ES.18) at Martigues, jointly responsible for 3.07 Mt CO_2 in the same year.

The cement sector is the dominating one in number of sources (6) and is responsible for only 2.76 Mt/y. Nevertheless, the industrial structure of the region is highly diversified, and there are sources in other sectors, including one the paper & pulp, hydrogen production, and non-iron metals factory, Energy-from-Waste and Chemicals (other). There are nine facilities in these sectors, totalling 2.08 Mt/y in 2018.



A clear trend of increasing or decreasing emissions in the region does not emerge from an analysis of the tendencies in each mapped facility. Although some cements factories and paper & pulp facilities show a tendency for decrease in the emission in the last three years, these are compensated by

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other facilities that are growing in CO_2 emissions. The large emitters in the Iron & steel and refineries sectors are either showing stabilised or irregular emissions patterns (Table 4-18).

Table 4-18 Main features of CO_2 emitting facilities in the Rhone Valley

Emitter ID	Facility name	Sector	City	Emissions (tCO_2/y)	Emission trend
FR2.ES.1	Arcelormittal Fos	Iron & Steel	Fos-sur-Mer	7460000	Irregular
FR2.ES.2	Raffinerie De Feyzin	Refineries	Feyzin	1120000	Stable
FR2.ES.3	Lafargeholcim Ciments - Usine Du Teil	Cement	Le Teil	603000	Growing
FR2.ES.4	Lafargeholcim Ciments - Usine De La Malle	Cement	Septèmes-les-Vallons	426000	Irregular
FR2.ES.5	Lafargeholcim Ciments - Usine Du Val D'Azergues	Cement	Lozanne	281000	Irregular
FR2.ES.6	Ciments Calcia Usine De Beaucaire	Cement	Beaucaire	535000	Growing
FR2.ES.7	Ciments Calcia Usine De Cruas	Cement	Cruas	95700	Falling
FR2.ES.8	Air Liquide Hydrogene Smr Lavéra	Hydrogen	Martigues	177000	Irregular
FR2.ES.9	Air Liquide France Industrie - Belle Etoile	Hydrogen	Saint-Fons	97000	Stable
FR2.ES.10	Raffinerie Esso	Refineries	Fos-sur-Mer	739000	Irregular
FR2.ES.11	Vicat	Cement	Montalieu-Vercieu	824000	Irregular
FR2.ES.12	Fibre Excellence Tarascon	Paper and pulp	Tarascon	640000	Falling
FR2.ES.13	Evere	Energy from waste	Fos-sur-Mer	397000	Stable
FR2.ES.14	Osiris Gie Roussillon	Other	Saint-Maurice-l'Exil	302000	Irregular
FR2.ES.15	Alteo Gardanne	Non iron metals	Gardanne	240000	Growing
FR2.ES.16	Adisseo Les Roches	Chemicals (other)	Saint-Maurice-l'Exil	119000	Falling
FR2.ES.17	Rhodia Operations - Etablissement Secondaire De Collonges	Chemicals (other)	Collonges-au-Mont-d'Or	104000	Falling
FR2.ES.18	Petroineos Manufacturing France Sas	Refineries	Martigues	1210000	Irregular

There is very scarce information about the main fuels utilised in the facilities, with natural gas being used in the two hydrogen production facilities and coke and coal being utilised in two cement plants.

CO_2 produced by processes other than fossil fuels combustion (such as emissions from combustion of biomass and waste) are relevant in seven installations, and totals around 1 Mt/y. This a very significant proportion and scenarios involving BECCS may be interesting for this promising region, specially at the Energy -from Waste "Evere" (FR2.ES.13) and the Paper and Pulp "Fibre Excellence Tarascon" (FR2.ES.12). Apart from these non-fossil fuel related emissions, the cement sector and the hydrogen production sector (the latter being based on natural gas reforming) have important process-based emissions, estimated at 60% for the cement industry and 100% for the hydrogen industry.

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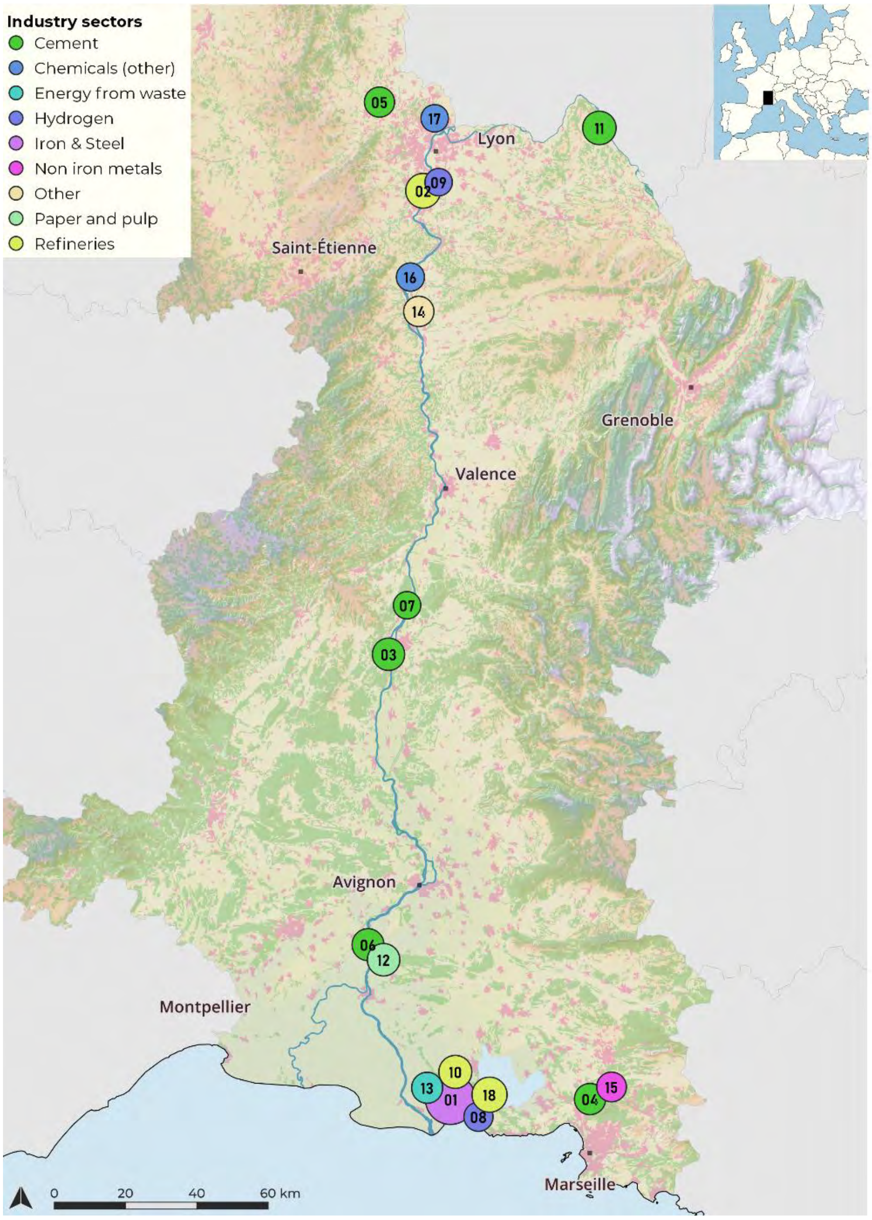

Figure 4-39 Location of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-18. For detail see map in Appendix I.

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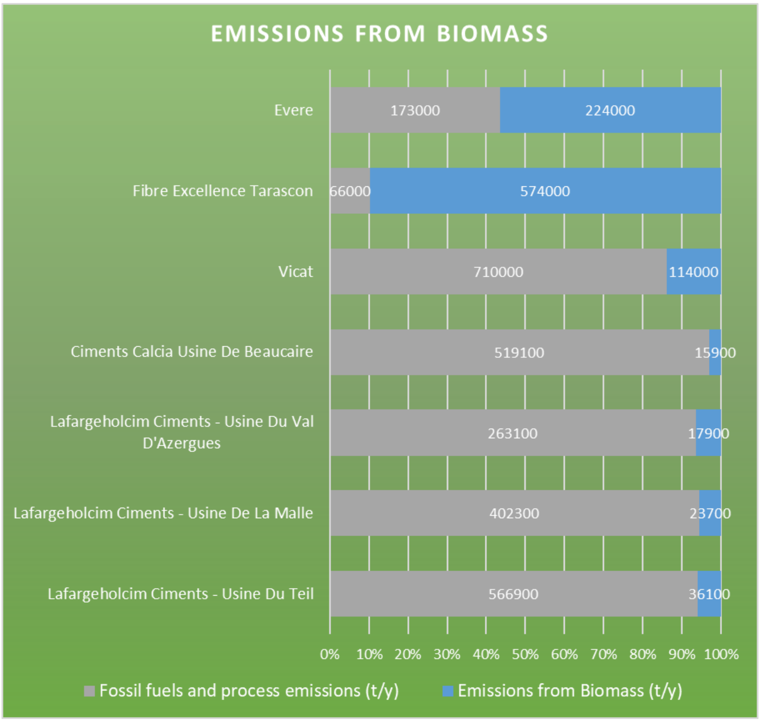
4.6.2 CO_2 Storage possibilities



The storage capacity assessment conducted in the Rhone Valley identified four structures in deep saline aquifers with a total storage capacity of 57.4 Mt at Tier 2 (daughter units) (Table 4-19). All storage units are composed by fractured limestones of the Middle to Late Jurassic and are located onshore, but very close the Mediterranean coastline (Figure 4-40).

Given that the eighteen selected sources in the Rhone Valley emitted almost 15 Mt in 2018 and that assessments for Tier 3 and Tier 4 will retrieve lower storage capacities, the identified storage capacity in the Rhone Valley is short for the needs of the industry in the region.

Furthermore, out the four storage units, only two have meaningful storage capacities, above 20 Mt. That does not mean that the two smaller storage units cannot be used, particularly if they are ideally located with respect to individual sources or groups of small-scale sources. However, the industrial activity in the region is very important and there are several high-level emitters, implying in practical terms, that the available structures can only be used by a few sources or one or two larger sources for a limited time.

Table 4-19 Main features of potential storage units in the Rhone Valley.

Storage Unit ID	Storage type	Storage Unit	Daughter unit	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)
FR2.SU.1	DSA	Upper Jurassic	Haut d'Abaron	fractured limestone	Onshore	200	865	24
FR2.SU.2	DSA	Upper Jurassic	Structure de Mas-de-Madame	fractured limestone	Onshore	492	800	22.8
FR2.SU.3	DSA	Upper Jurassic	Structure de Saintes-Maries-de-la-Mer	fractured limestone	Onshore	1443	285	9.7
FR2.SU.4	DSA	Jurassic - Dogger	Structure de Cicendèle	fractured limestone	Onshore	559	153	0.9

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4.6.3 Spatial conditions for cluster and network development

The spatial distribution of the sources along the Rhone Valley, despite being spread along the 250 km length of the valley, actually forms an ideal ICCUS cluster, with smaller sources grouped around Lyon, mostly in the cement, chemical and hydrogen sectors, that can be easily connected to two other cement factories down the river in Montélimar and one cement and one paper & pulp mill at Beaucaire, to finally join the large-scale emitters at the estuary of the Rhone, west from Marseille, where the potential storage sites are (Figure 4-41).

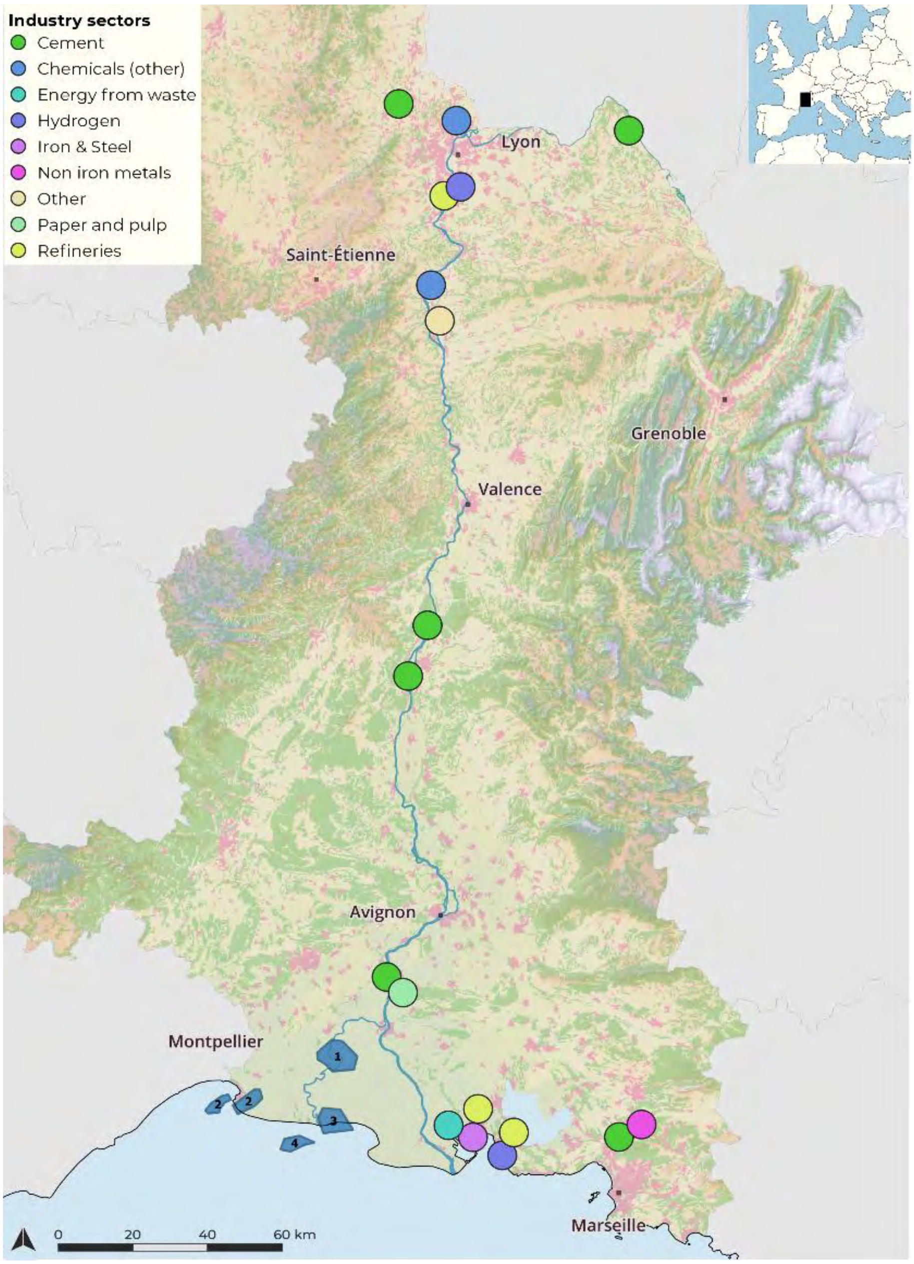

Figure 4-40 Potential storage units in the Rhone Valley, shown as blue polygons at the Mediterranean coastline. Numbers represent the unit ID in Table 4-19. For detail see map in Appendix I.

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The valley of the Rhone defines a transport corridor, with many of the sources being located a few hundreds of meters away from the river, and sometimes with port terminals adjacent to the sources. Parallel to the Rhone runs a railway line and the main roadways, so that distances from the facilities are also small. Still, among the eighteen sources with the highest potential for CO_2 capture there are several large-scale emitters, so that transport in liquid form, using river barges for instance, is feasible only for a small few sources with small emissions, such as the "Ciments Calcia Usine de Cruas", FR2.ES.7, (0.095 Mt/y) or "Air Liquide France Industrie - Belle Etoile", FR2.ES.9, (0.097 Mt/y).

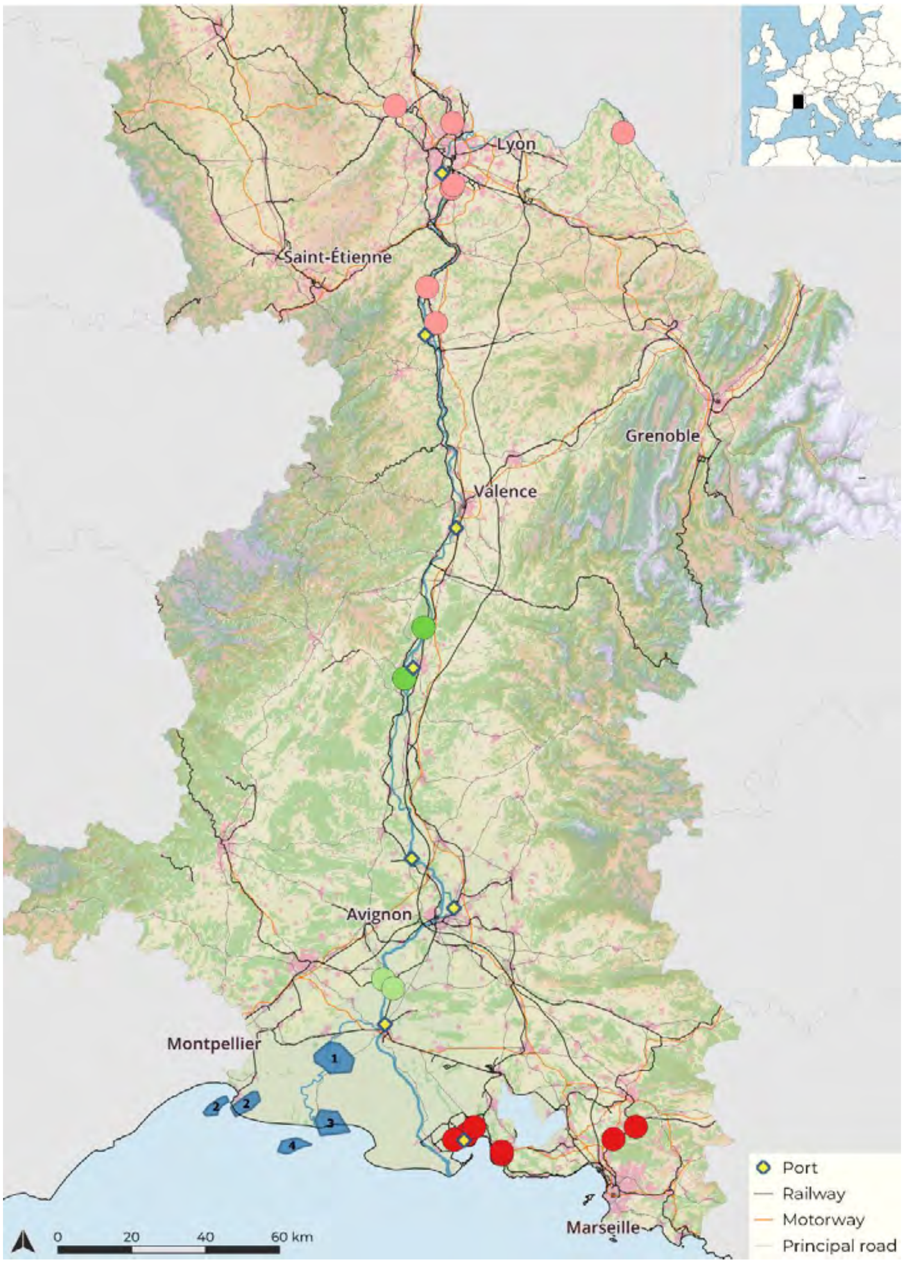

Figure 4-41 Clustering of CO_2 emitters and location of possible transport modes (roads, railways and ports). Pink represents the Lyon cluster, light green the Montélimar sources, pale green the Beaucaire sources and red the Marseille cluster.

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There is no CO_2 pipeline corridor defined in the area, but there is a natural gas pipeline running along the valley of the Rhone, from Lyon to Marseille. Reutilisation of the pipeline (if it is possible in the future) or using the same corridor for a purposely built CO_2 pipeline could provide a trunk transport solution from the northern part of the basin to the Mediterranean coastline.

The sources are grouped according to clusters that could collect and consolidate CO_2 in a local hub before joining the trunk pipeline to the coast. In and around Lyon there are seven sources with an estimated capture volume of 2.56 Mt/y, including the "Raffinerie de Feyzin" (FR2.ES.2), the second largest source in the Rhone Valley, two cements plants, one hydrogen production facility and three chemical related installations. The refinery and the "Vicat" cement plant (FR2.ES.11) clearly dominate the cluster, with joint emissions of 1.94 Mt/y.

The region of Lyon is highly urbanised, but the sources are either outside the city limits or are installed in industrial polygons, where space for building capture facilities is probably available.

In general, each of the point sources around Lyon has multiple options for CO_2 collection and transport to a common consolidation hub, possibly outside Lyon, near the Feyzin refinery. The largest sources will require transport by pipeline to the hub, but minor sources could use liquid phase transport along the waterway. In any case, the collection network would be relatively small as sources are not very distant from each other.

The exception is the "Vicat" cement factory. This source some 40 km in linear distance from the existing natural gas pipeline. It is set in the margins of the Rhone, upstream from Lyon, but the emissions volumes (1 Mt in 2018) are too high to consider waterway transport, so that a longer pipeline is required for collection and consolidation at a hub outside Lyon.

A second group of emission sources emerges around Marseille, including seven sources with a capture potential of 9.58 Mt/y, and dominated by the "ArcelorMittal FOS" Iron&steel mill (FR2.ES.1) and "Raffinerie ESSO " (FR2.ES.10) and the "Petroineos Manufacturing France SAS " (FR2.ES.18) refineries at Fos-sur-Mer and Martigues. The cluster also includes an Energy from Waste power plant, a hydrogen production facility, one cement factory and one non-iron metals processing plant, but these four sources represent 10% of the emissions from the iron&and steel mill and the refineries.

All sources in this cluster are outside city limits and in well-defined industrial polygons, so that space constraints for building new facilities should not be a problem. They are spread along an E-W alignment extending for some 40 km, but the three main sources are not more than 9 km apart, at Fos-sur-Mer and Martigues, and could provide the locus for an ICCUS cluster.

The sources in this cluster are well connected to railway lines, and the largest ones have dedicated railway branches and, those that are located at the Mediterranean shore, have also dedicated port facilities. Furthermore, all sources are connected by existing natural gas pipelines, the corridor of which may be a good option to transport CO_2 from those sources further away in the cluster, the "ALTEO Gardanne" non-iron metals facility (FR2.ES.15) and the "Lafargeholcim Ciments - Usine De La Mall" (FR2.ES.4), to the Fos-sur-Mer and Martigues consolidation hub.

This cluster around Marseille, if consolidated in a hub at Fos-sur-Mer or Martigues is not distant from the storage units identified in the Upper Jurassic. Trunk transport could be done by pipeline to

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the injection sites, but since the storage capacity is limited (about 4 to 5 years of the emissions from the three larger sources), other strategies need to be considered for transport to other storage locations.

Along the Rhone valley, 120 km downstream from Lyon and 130 km upstream from the mouth of the river, there are two cement factories in Montélimar, the “Ciments Calcia Usine de Cruas” (FR2.ES.7) and the “LafargeHolcim Ciments - Usine du Teil” (FR2.ES.3), the former a relatively small CO_2 source (95.7 kt/y), but the latter an important source (0.6 Mt/y). Distancing 15 km from each other, they are in rural setting and right at the margins of the Rhone and have dedicated piers, so that the possibility of transport along the river should be considered, at least for the smaller source.

A similar situation can be found at Beaucaire, even further south along the Rhone, at about 50 km from the Rhone estuary. At the left bank of the river there is a pulp & paper mill “Fibre Excellence Tarascon” (FR2.ES.12) emitting 0.6 Mt/y in 2018, while next a canal connecting to the river is the “Ciments Calcia Usine de Beaucaire” (FR2.ES.6) cement factory (0.5 Mt/y). This area presents the same transport options as the sources in Montélimar.

Certainly, the development of a CO_2 transport network in the Rhone Valley is well served by multiple transport possibilities, with the topography of the valley defining a north-south network along which the river, roads, railways and natural gas pipelines are installed. Despite the long transport distance from the northernmost sources in Lyon to the sources in Marseille, around 250 km, several transport solutions can be studied for feasibility. Nonetheless, the issue is where to store the CO_2? The geological storage capacity estimated in the four storage units near the mouth of the river is insufficient for the local needs, and perhaps the transport network along the Rhone Valley should be directed to the port Marseille-Fos for transport to other storage locations.

4.6.4 CO_2 utilisation options

Regional plans of territory development do not mention carbon capture and utilisation (neither storage, except for “natural sequestration” in soils and forests). However, the Provence-Alpes-Côte d’Azur Region (around Marseille) already mention the utilisation of CO_2 in a few documents.

Moreover, both the “Auvergne-Rhône-Alpes” (AURA) administrative region and the Marseille metropole display the ambition of developing the hydrogen sector. AURA set objectives of decarbonised mobility deployement (hydrogen, electric, BioNGV). Marseille Metropole has a “H2 strategy” to structure the sector and to become the Mediterranean hub of hydrogen.

4.6.4.1 On-going CCU projects

There are currently four ongoing projects linked to carbon capture and use, one in the north of the Rhône Valley close to Lyon, the other three in the south of the valley close to Marseille:

CimentAlgue - Algae production from CO_2 at the “VICAT” cement plant at Montalieu-Vercieu, close to Lyon. Various microalgae culture systems are being tested over a two-year period.

$VASCO_2$ - Algae production from CO_2. Launched in the autumn of 2015, $VASCO_2$ is a research programme led by the port of Marseille-Fos with twelve partners (industrialists from the industrial-port zone of Fos, research centres, VSEs, institutions) aiming to valorise the CO_2 emitted by industry.

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Their ambition: to contribute to the energy transition through innovation by testing a novel solution to produce biomass based on the biological recycling of industrial CO_2.

Jupiter 1000 - Power to gas (methane). The Jupiter 1000 project is the first industrial demonstrator of Power to Gas with a power rating of 1 MWe for electrolysis and a methanation process with carbon capture. Green hydrogen will be produced using two electrolysers involving different technologies, from 100% renewable energy. The installation will be based on an innovative methanation technology and CO_2 will be captured on a nearby industrial site. The project is located at Fos-sur-Mer, on the Innovex platform dedicated to hosting demonstrators related to the Energy Transition, and at the intersection of gas and electricity networks. In the light of the performance levels shown by the demonstrator, further work will focus on future technical and economic standards of a full-sized installation of this type. Over the longer term, the idea is to launch the Power to Gas activity in France. More than 15 TWh of gas could be produced each year using the Power to Gas system by 2050.

HYBIOL - Biomethanol production from CO_2 and green H2 at the Gardanne-Meyreuil biomass plant site. Hybiol is a reconversion project for the Gardanne-Meyreuil power plant site with a view to the closure of coal boilers announced by the State by 2022. The project would contribute to the development of a territorial ecosystem with a circular economy of reference.

4.6.4.2 Carbon use perspective in Rhone Valley

Chemistry sector

The northern Rhone valley (around Lyon) is known as the "Chemistry valley" with many chemical plants settled there. This allows interactions between plants and mutualised infrastructures. For example, the gas production plants of AirLiquide (Feyzin, Belle-Etoile) provides hydrogen and nitrogen to the chemical plants in the region via km of pipelines. There could be a potential for such an organisation for CO_2, as CO_2 is used in chemical industry.

At a smaller scale, on the Roussillon site (platform gathering chemistry plants in the south of Lyon) a fine chemistry plant (NOVACYL, producing methyl salicylate) uses for its process the CO_2 emitted by the next-door hydrogen plant (AirLiquide). CO_2 needs are around 10kt/y.

Fuels

The port area of Marseille involves petrochemistry industry that can offer potential for carbon use for biofuels. Given the political objectives in the region for hydrogen sector deployment, there is a high potential for carbon utilisation in this branch.

Algae

There are already two projects in the region (one in the Lyon region, one in the Marseille region).

Building materials/carbonation

The FastCarb (Accelerated carbonation of recycled concrete aggregate) project aims to valorize both recycled concrete aggregates (from building deconstruction) and CO_2 emitted during the clinker production. Indeed, recycled concrete aggregates can react with CO_2 to form carbonates. The carbonates formation allows reducing the aggregates' porosity, which improves its properties. The

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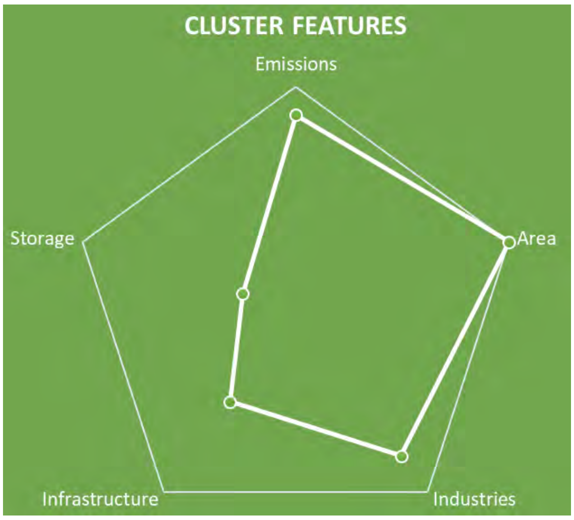
project aims to determine the best process for carbonation by considering the process efficiency and the cost.

Solidia is developing a new process to manufacture precast concrete, with CO_2 used to make calcium carbonate and silica to harden the concrete structure. The process allows lower concrete's carbon footprint by up to 70% compared to a classical Portland cement. The CERIB is testing the process and concrete properties.

4.6.5 Main features of technical potential for ICCUS development

The Rhone Valley presents, in what relates to emissions and transport features, excellent prospects for developing an ICCUS cluster. The high level of emissions from many different types of industry and their concentration in two main industrial areas, in Lyon and Marseille, are the strongest motivators for engaging in CCUS implementation. In particular, very large sources in Fos-sur-Mer and Martigues, near Marseille, could act as an aggregator for developing CCUS in the regions, since that area alone emits around 9 Mt/y, roughly 50% of all the emissions in the Rhone Valley.

There is a wide range of transport opportunities for CO_2, provided by the Rhone valley along which the pipelines, railways, roadways and waterways align, and provide options for collecting the CO_2 from the sources around Lyon, gathering the emissions from the sources further south in Montélimar and Beaucaire, and ultimately joining the large industrial area of Fos-sur-Mer and Martigues at the mouth of the Rhone. The river itself could be a good option for transport for smaller sources. The existing natural gas pipelines could provide an opportunity to follow the same corridors with a dedicated CO_2 pipeline network for trunk transport to the south.



However, the storage capacity identified so far is insufficient to consider large scale injection of CO_2 compatible with the existing emissions in the area. The Tier 2 storage capacity assessment identified only 57.4 Mt of capacity in four limestone structures, and this value is set to decrease as the detail in analysis increases. Either storage capacity is identified in other geological formations in the Rhone Valley, or scenarios for large-scale implementation of ICCUS in the Rhone Valley needs to consider transport to other regions.

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Table 4-20 Rhone Valley cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	Two main loci: Lyon and Marseille. At Marseille, refineries (2), steel mill (1), cement factory (1), hydrogen (1), energy from waste (1) and non-iron metals facility (1). By the far the largest emitting area in the region. At Lyon, smaller sources, but also one refinery and one large cement factory. Four other relevant sources spread in Montémillar and Beaumaire.	+
	Emission volume distribution	Three sources around Marseille (steel mill and two refineries) concentrate 50% of the total emissions 18 Mt/y. Around Lyon lower emissions, but still relevant (2.56 Mt/y)	+
	Emission volume profile	Not clear, some cement factories with a decreasing trend, but other sources with increasing emissions, Most sources stable or irregular.	~
	Emissions type and quality	Mostly fossil fuel combustion emissions, but combustion of biomass and waste account for around 1 Mt/y. The cement sector and the hydrogen sector present high-level process emissions. No high concentration sources.	+
AREA	Industrial area character	Large industrial areas in Fos-sur-Mer and Martigues, near Marseille, and at Lyon. Usually outside city limits, in industrial polygon or in rural areas.	+
	Importance of industry	Marseille is a major industrial area, large supply chain supported by heavy industries and docks. Industry also very important around Lyon.	+
	Cluster recognition	Area had previously been included in clusters in project VASCO	+
INDUSTRIES	Integration of industry	Refineries, steel mill and hydrogen production seem to share industrial polygons in Fos-sur-Mer and Martigues. Many of the sources, particularly in the cement sector, seem to have the same company owners.	+
	Decarbonisation alternatives	Not identified.	~
	CCU	CO_2 utilisations in the important chemical sector in the region is a strong possibility, has is the production of synthetics fuels in the refineries in the area. Mineral carbonation in the several cement plans also interesting.	+
	Motivation for decarbonisation	National strategies for climate mitigation	~
	Motivation for CCS	Highly industrialised area, CO_2 emission reduction very important for maintaining competitiveness of the region and maintain jobs.	+
INFRASTRUCTURE	CO_2 collection options	Transport along the Rhone River is an option for some small sources, but generally new pipeline network is required.	+
	CO_2 consolidation options	No major constraints seem to exist for implementation of consolidation hubs, since sources are in industrial polygons or rural areas	+
	Existing CO_2 infrastructure	No existing infrastructure.	–
	Infrastructure reuse options	Existing pipelines likely to continuing running natural gas, unlikely to be available for reuse.	-
STORAGE	Storage accessibility	Storage sites onshore are more than 250 km distant from sources in the Lyon and around 30-50 km from the Marseille sources. No existing pipeline network to the storage sites.	-
	Storage capacity	Small capacity, only 57.4 Mt for a Tier 2 assessment. Insufficient for long term needs of the region.	-
	Storage flexibility	Very small, since only two structures have a meaningful storage capacity above 20 Mt.	-
	Storage development integration	Project VASCO involved many of the main emitters in the region to plan for industrial CCS valorisation in the region, including ArcelllorMittal, Air Liquide, GDF, EDF Suez, and others	+

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4.7 Upper Silesia – Poland

4.7.1 Emissions and industry sectors

Upper Silesia is the promising region with the highest CO_2 emissions in STRATEGY CCUS, totalling 30.4 Mt/y in 2018, from fourteen sources each with annual emissions above 100 kt. Such a high carbon intensity is due to the utilization of coal as the main fuel. From the fourteen sources, nine are power plants running exclusively on coal, with emissions ranging from 0.61 Mt/y for the “Elektrocieplownia Bedzin” plant (PL.ES.11), to 6.48 Mt for the “Elektrownia Rybnik“ power plant (PL.ES.11). Two other power plants run on coke gas and consequently show lower emissions, from 0.12 Mt/y to 0.23 Mt/y, while another power plant burns biomass and coal and emitted 0.9 Mt in 2018.

Thus, the power sector is overwhelmingly the most important in this promising region, responsible for 83% of the emissions, the remainder being emissions from an Iron & steel plant “Ironworks Arcellor Mittal” PL.ES.4 (4.64 Mt/y), and one coke production plant, PL.ES.12 (0.43 Mt/y) (Figure 4-42).

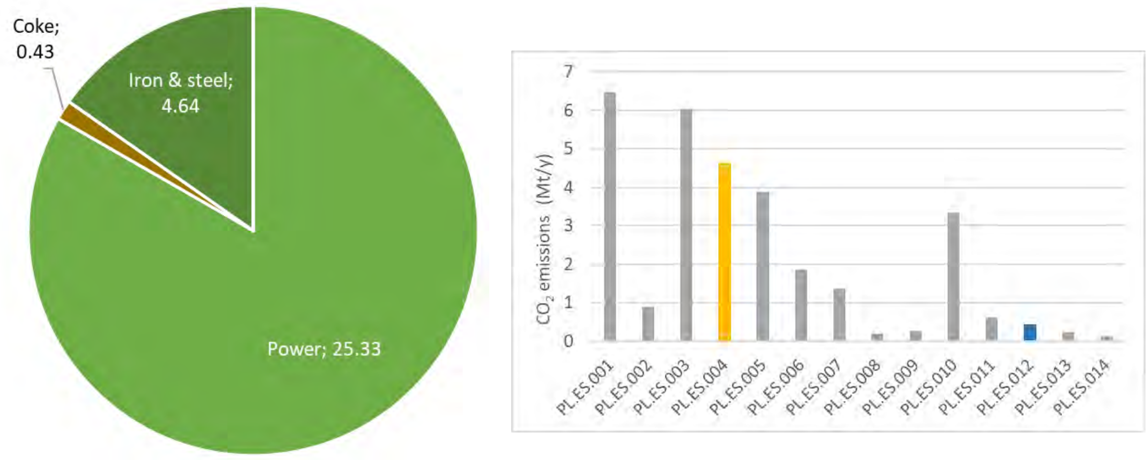

Figure 4-42 Emissions (in Mt/y) per sector and per facility thee Upper Silesia. In the bar chart: grey are power plants, yellow is an iron & steel mill and blue is a coke producing plant. *Emitter ID* according to Table 4-21.

Although the sources are spread across the entire Upper Silesia promising region, there is a higher concentration of sources around the cities of Dabrowa Gornicza, Jaworzno and Katowice, in which 13 sources are concentrated in an area less than 200 km^2, including the second and third largest sources in the region, the Tauron Power plant at Jaworzno (PL.ES.3) and the ArcelorMital facility (PL.ES.4) at Dabrowa Gornicza.

The other three sources are in the south of Upper Silesia and more isolated from each other, being the only large sources in the cities Rybnik, Tychy and Laziska Gorne.

The coal power plant “Elektrownia Rybnik” (PL.ES.1), the largest emitter with 6.48 Mt/y is seeing, nevertheless a decreasing trend in emissions in recent years, as does the “Tauron” power plant at Bedzin (PL.ES.6). All other sources show a stabilisation of emissions, except for the “Elektrociepłownia“ (PL.ES.11) power plant at Bedzin where emissions are increasing (Table 4-21).

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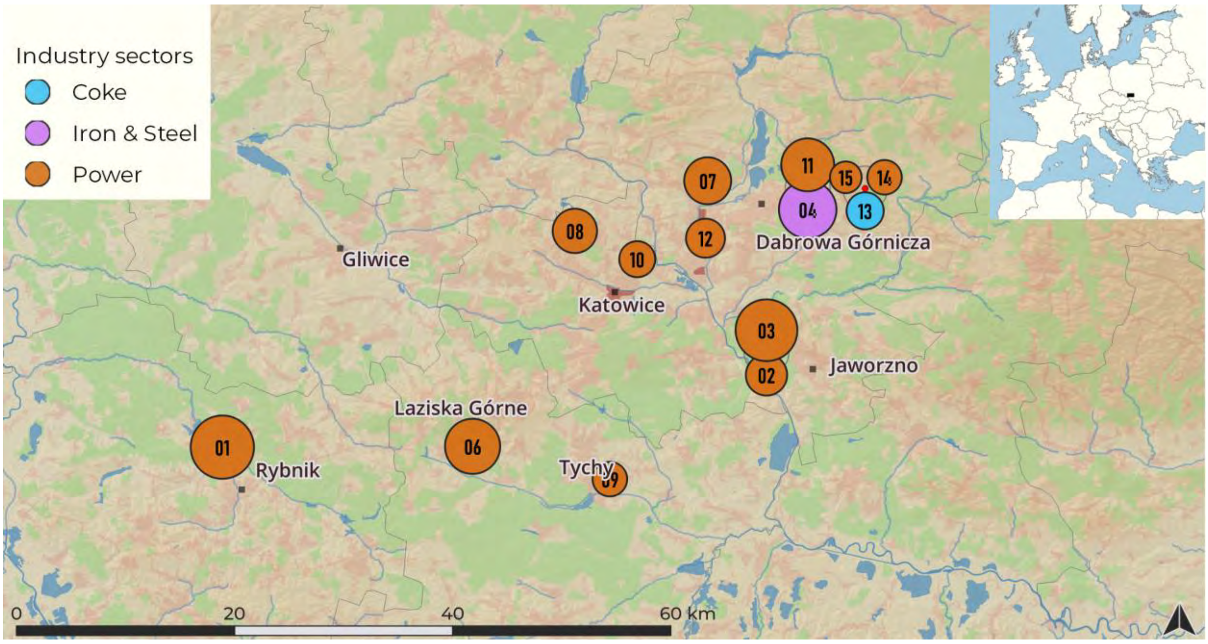

Figure 4-43 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-21. For detail see map in Appendix I.

Table 4-21 Main features of CO_2 emitting facilities in the Upper Silesia

Emitter ID	Facility name	Sector	Location	Emissions (tCO_2/y)	Emission trend	Main fuel
PL.ES.1	Elektrownia Rybnik	Power	Rybnik	6480000	Falling	coal
PL.ES.2	TAURON Wytw. SA Elektr. Jaworzno III Elektr. II	Power	Jaworzno	912450	Stable	biomass /coal
PL.ES.3	TAURON Wytwarzanie SA O. Elektrownia Jaworzno III	Power	Jaworzno	6041100	Stable	coal
PL.ES.4	Ironworks Arcellor Mittal	Iron & Steel	Dąbrowa Górnicza	4643350	Irregular	coke, coal
PL.ES.5	TAURON Wytwarzanie SA O. Elektrownia Łaziska	Power	Łaziska Górne	3879920	Stable	coal
PL.ES.6	TAURON Wytwarzanie SA O. Elek. Łagisza w Będzinie	Power	Będzin	1869428	Falling	coal
PL.ES.7	CEZ Chorzów S.A.	Power	Chorzów	1354248	Stable	coal
PL.ES.8	Elektrociepłownia Tychy	Power	Tychy	203801	Stable	coal
PL.ES.9	Elektrociepłownia Katowice	Power	Katowice	273898	Stable	coal
PL.ES.10	Zakład Wytwarzania Nowa	Power	Dąbrowa Górnicza	3339922	Stable	
PL.ES.11	Elektrociepłownia Będzin Sp. z	Power	Będzin	609922	Growing	coal
PL.ES.12	Koksownia Przyjaźń	Coke	Dąbrowa Górnicza	431026	Stable	coal
PL.ES.13	Elektrownia Koksowni Przyjaźń	Power	Dąbrowa Górnicza	234962	Stable	coke gas
PL.ES.14	Elektrociepłownia Koksowni Przyjaźń	Power	Dąbrowa Górnicza	126247	Stable	coke gas

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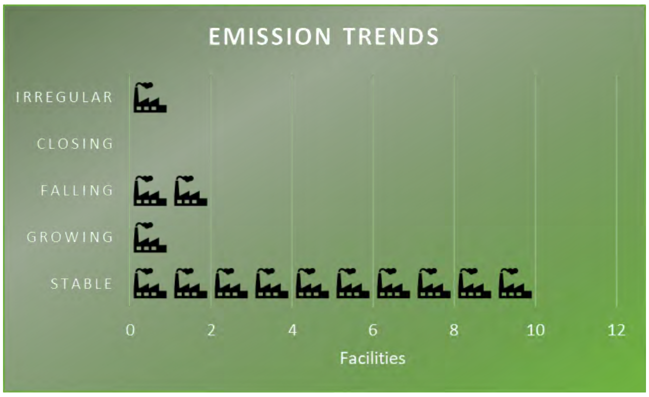

CO_2 produced from biomass combustion has not been reported, but it surely exists at Jaworzno "Tauron" facility, since biomass is reported as one of the fuels used in the facility. Fuel switch to biomass is the main decarbonisation alternative available and it is currently being considered at the "Tauron" plant at Tychy, perhaps raising the oportunity for BECCS, while at "CEZ Chorzów S.A." adding waste to the fuel mixing is being considered. Replacement of coal with gas from metallurgical processes is also being planned at "Tameh" plant at Dąbrowa Górnicza. Switch from coke gas to hydrogen is a decarbonisation alternative suggested at JSW Koks SA coke furnace (PL.ES.012), also at Dąbrowa Górnicza.

Process emissions are negligible for all the power plants and coke production plant, but may be relevant for the ArcellorMittal iron & steel mill at Dąbrowa Górnicza.

4.7.2 CO_2 Storage possibilities

Upper Silesia is the only STRATEGY CCUS promising region where Uneconomic Coal Beds (UCB) are a geological storage option, in the Upper Silesia Coal Basin. The "Studzienice-Miedzyrzecze" unit (PL.SU.1) has an estimated storage capacity of 6.96 Mt, while the Pawlowice-Mizerow prospect (PL.SU.2) has a capacity of 8.43 Mt. Albeit this storage capacity should not be neglected for injecting CO_2 from individual small-scale sources, the full capacity in the UCB is certainly insufficient (Table 4-22).

Storage capacity has also been identified in Deep Saline aquifers, namely in Miocene Deposits of the Upper Silesian Coal Basin (PL.SU.3), with a total capacity of 46.2 Mt, and in marine deposits of the Jurassic Czestochowa District (PL.SU.2), where the capacity is estimated at 50 Mt (Table 4-22). In both storage units, the estimates were made at Tier 1 for specific case studies in the basins.

Hence, the total estimated storage capacity in the promising region is 111.5 Mt. All potential storage locations are located onshore, at distances from the CO_2 sources varying from less than 10 km to the UCB targets to more than 100 km from the southernmost sources to the DSA in the Jurassic Czestochowa District (JCD) (Figure 4-44). Given that the current emissions in the mapped sources are above 30 Mt/y, that the average emissions per source is on the order of 2.2 Mt/y and that assessments for Tier 3 and Tier 4 will most certainly retrieve lower storage capacities, it is unlikely that the Upper Silesia promising region has the capacity required to store its CO_2 emissions for a meaningful period of time.

Obviously, the Deep Saline Aquifers provide sufficient capacity to store CO_2 from some of the sources, particularly for those better located with respect to individual storage units, but if CCUS is to have an impact in the CO_2 release avoidance in Upper Silesia, a CCUS network needs to consider the possibility of transport to other regions of Poland or other countries to ensure enough storage capacity.

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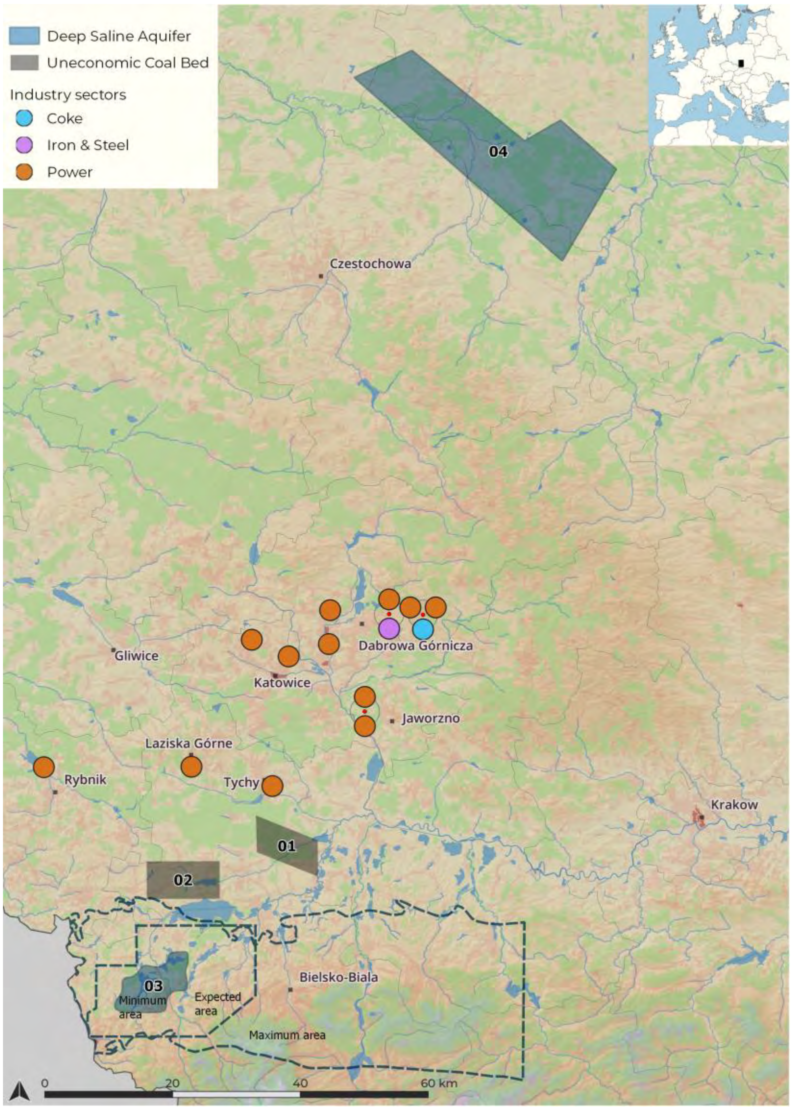

Figure 4-44 Potential storage units in Upper Silesia. Numbers represent the *unit ID* in Table 4-22. For detail see map in Appendix I.

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Table 4-22 Main features of potential storage units in Upper Silesia.

Storage Unit ID	Storage type	Storage_Unit	Daughter unit	Formation	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)
PL.SU.1	UCB	Upper Silesian Coal Basin (USCB)	Studzienice-Międzyrzecze	Carboniferous	Orzesze Beds, Ruda Beds: Typical cyclic coal-bearing rocks in which off-channel fine-grained sediments (80%) prevail over sandstones. Coal seams are numerous, thin and variable.	Onshore	1350	865	6.96
PL.SU.2	UCB	Upper Silesian Coal Basin (USCB)	Pawłowice-Mizerów	Carboniferous	Orzesze Beds, Ruda Beds: Typical cyclic coal-bearing rocks in which off-channel fine-grained sediments (80%) prevail over sandstones. Coal seams are numerous, thin and variable.	Onshore	1400	800	8.34
PL.SU.3	DSA	Upper Silesian Coal Basin (USCB)	Cieszyn-Skoczów-Czechowice	Miocene deposits (Dębowiec Beds)	Miocene macroclastic molasse composed of four lithofacies: olistostromes, boulders, conglomerates and sandstones	Onshore	750 - 1300	285	46.2
PL.SU.4	DSA	Jurassic Częstochowa District (JCD)	Częstochowa region	lower Jurassic shallow marine deposit	fine to coarse and various grain sandstones	Onshore	1000-1500	153	50

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4.7.3 Spatial conditions for cluster and network development

The spatial distribution of the CO_2 and geological storage sites, leads to consider three groups of sources, one in the east, centred around Dąbrowa Górnicza - Jaworzno, a second one in the centre of the promising region, at Katowice, in very close proximity to the previous cluster, and a third one in the south, close to the Upper Silesia Coal Basin (Figure 4-45).

The nine sources in the Dąbrowa Górnicza - Jaworzno group are responsible for emissions of 18.2 Mt/y, 60% of the total, and admitting a minimum capture rate of 85%, could provide annual capture volumes of around 12 Mt. At Dąbrowa Górnicza, the ArcellorMittal iron & steel mill (PL.ES.4) and the "Tameh " power plant (PL.ES.11) are located in the same industrial complex, which is distant by only a couple of kms from the "JSW Koks SA" industrial complex where two power plants (PL.ES.14 , PL.ES.15) and one coke production plant (PL.ES.13) are operating (Figure 4-46). Given the proximity of these sources and likely similarities in flue gas stream properties (at least for some sources), synergies may exist in terms of capture and transport facilities.

South from Dąbrowa Górnicza, at Jaworzno, a similar situation occurs with the two "Tauron" power plants (PL.ES.2, PL.ES.3) which are at contiguous industrial complexes, distancing less than 1 km, perhaps with the possibility to share capture and transport facilities (Figure 4-46). These sources are around 14 km south from those in the Arcellor Mittal and JSW Koks SA complexes. Although being connected to the Dąbrowa Górnicza sources by the ubiquitous railway network in Upper Silesia, and having dedicated rail terminals at the site, the emissions are too high to consider for a CO_2 collection mode other than pipelines.

Still within the same group of sources, but 7 km east from the Arcellor Mittal industrial complex, the "Tauron Bedzin" and the "Elektrocieplownia Bedzin" power plants are isolated sources. They are again in industrial complexes, so that spatial constraints for building capture and compression facilities, should not be a problem, as for all other sources in Dąbrowa Górnicza and Jaworzno.

The two sources at Będzin can also connect to the sources in Jaworzno and in the industrial complexes of Arcellor Mittal and JSW Koks SA, again by a pipeline collection network, since the emissions are too high for transport in liquid-phase.

Given the location of this group of sources, consolidation of CO_2 could occur in a hub near the ArcellorMittal and JSW Koks SA complexes, before trunk transport to the Czestochowa deep saline aquifer, 60 km north of Dąbrowa Górnicza. Nevertheless, the existing capacity in this storage unit is insufficient for a long-term injection project, so that transport outside Upper Silesia may need to be considered. Due to the large volume of CO_2 produced in these sources, trunk transport most likely requires a purposely built pipeline, as existing pipelines are not available to transport CO_2.

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The second group of sources is composed by the "Tauron" power plant at Katowice (PL.ES.10) and the "CEZ Polska" power plant (PL.ES.8) at Chorzów, about 6 km apart, but connected by the same railway line. These two sources share a common option for transport by waterway along the Gliwice canal to each both could connect at Gliwice, 25 km away from Katowice (Figure 4-47). Perhaps this could be a valid alternative, because these two sources are not so carbon intensive as those in Dąbrowa Górnicza - Jaworzno, with a possible capture volume of around 1.4 Mt/y. Another option would be to connect to a consolidation hub shared with the Dąbrowa Górnicza-Jaworzno group of sources, before being transported by a trunk pipeline to the Baltic ports and to offshore storage.

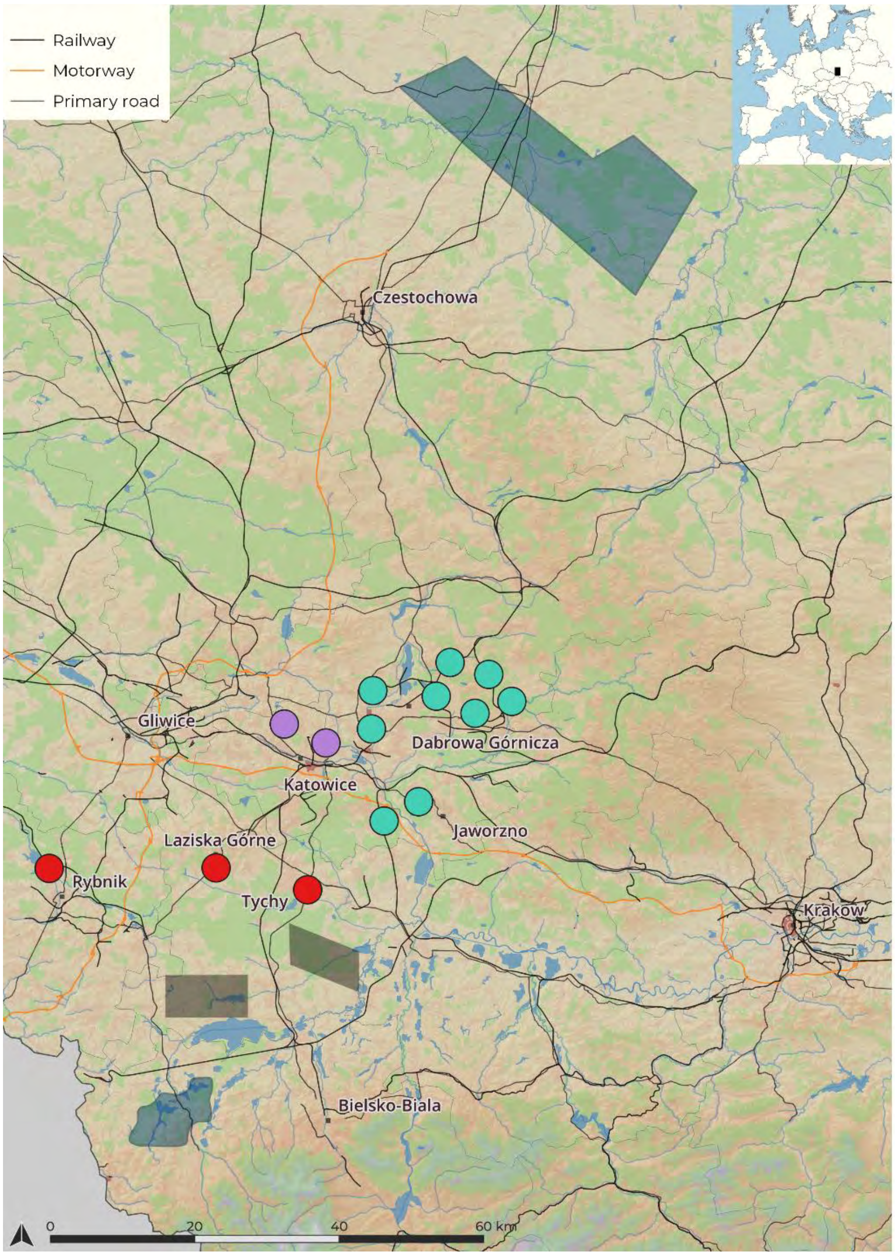

Figure 4-45 Clustering of CO_2 emitters and location of possible transport modes (roads, railways and ports). Green blue represents the Dąbrowa Górnicza - Jaworzno cluster, purple the Katowice sources, red the southern cluster.

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The southern group of sources, comprising the "Tauron" power plants at Tychy (PL.ES.9) and at Laziska Gorne (PL.ES.6) and the "PGE GiEK S.A." power plant (PL.ES.1) at Rybnik, spreads along an east-west 36 km line north of the Upper Silesia coal basin. The obvious storage targets would be the DSA and the UCB in this basin. The "PGE GiEK S.A." power plant is the largest emitter in Upper Silesia, with reported emission of 6.48 Mt in 2017, while the Laziska Gorne "Tauron" facility emits a further 3.9 Mt/y. These two sources alone emit more than 10 Mt/y. The facility at Tychy is much smaller, with emissions of around 0.2 Mt/y.

Given the low storage capacity of the saline aquifer in the region, around 46 Mt at Tier 1 assessment, storage of the total volume from the three sources is not feasible, unless further storage capacity is found in other deep saline aquifers in the basin. Note that the capacity provided by the UCB is not only residual, but also injection of CO_2 in coal seams is at a much lower level of maturity than storage in saline aquifers.

Alternatives need to be found, perhaps by transport via pipeline to a consolidation hub at Laziska Gorne or Tychy, and follow a trunk pipeline to join the CO_2 captured from the sources in Dąbrowa Górnicza -Jaworzno or from sources around Katowice. For the smaller source in this cluster utilisations of CO_2 in the Upper Silesia could be, at least, part of the solution. The Tauron's facility at Tychy (PL.ES.9) could supply the Synthos chemical facilities at Oswiecim, only some 17 km away, and with options of transport in liquid phase by railway or road.

Figure 4-46 Left: Sources in the ArcellorMittal and JSW Koks SA industrial complexes. Right: location of Tauron's facilities ate Jaworzno.

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Figure 4-47 Sources at Katowice, also showing the railway line connecting the sources to the Gliwice canal to the west.

4.7.4 CO_2 utilisation options

The Polish National Centre for Research and Development funded research project related to capture carbon dioxide from flue gas under the 2010-2015 strategic program "Advanced energy technologies". However, there is a lack of CO_2 utilisation plans in national governmental strategies and plans, namely the Polish Energy Policy, National Environmental Policy, National Energy and Climate Plan. Regional plans, such as the *Strategy for Responsible Development - Program for Silesia, 2017* mentioned developments in the field of clean coal technologies, alternative forms of coal mining, and CO_2 capture, use and storage.

Industry has been more active, notably the second largest polish energy group, the Tauron Wytwarzanie S.A. based in Upper Silesia, in Jaworzno, which is engaged in research on CO_2 capture and conversion. In what regards CO_2 capture Tauron implemented:

- Lagisza Power Plant – adsorption DR-VPSA (Dual-Reflux Vacuum-Pressure Swing Adsorption), hard coal, fluidized bed boiler for supercritical parameters 460 MWe, 100 m^3n/h of flue gas, 13% CO_2, capture rate 90%;
- Laziska Power Plant – A Pilot Amine-Based CO_2 Capture Plant (hard coal, pulverised bed boiler 200 MW, 200 m^3n/h of the flue gas, 13,5% CO_2, capture rate 90%); years 2013-2014

On CO_2 utilisation, Tauron invested in conversion technologies: a mobile installation prepared under KicInnoEnergy CO_2-SNG project. This methanation project relies on conversion of carbon dioxide captured from flue gas and hydrogen produced by an electrolyzer to produce synthetic natural gas (SNG). The CO_2-SNG plant is located at the Laziska Power Plant, where a pilot amine-based CO_2 capture plant has already been tested. The stream of CO_2 used in this project is 4.5 Nm^3/h, with a carbon conversion rate to SNG of 93%. Details can be found on the website https://www.tauron-wytwarzanie.pl/innowacje/co2-sng.

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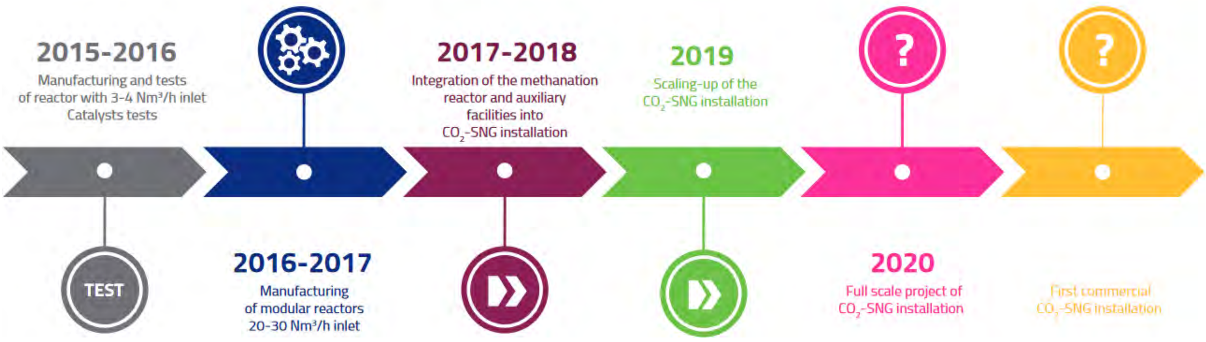


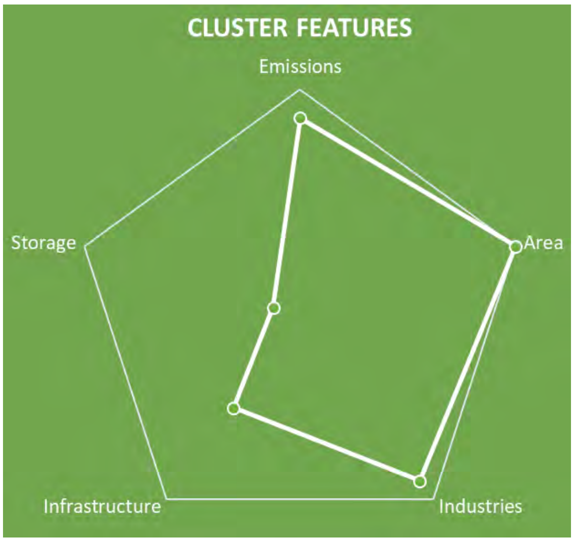
Figure 4-48 Timetable for development of the project CO_2-SNG undertaken by Tauron (Tauron, 2020)

Although CO_2 utilisations in the chemical sector are not yet planned or implemented, the existence of an important chemical sector in the Upper Silesia region, operated by SYNTHOS in Oswiecim, should not be discarded in terms of possible uses of the CO_2 captured at nearby sources, such as at the Laziska Tychy Tauron's plant.

4.7.5 Main features of technical potential for ICCUS development

Upper Silesia has important motivations for the engaging in ICCUS, since the power sector is based in coal combustion, and coal mining is an essential economic activity in the region. Deploying CCUS would allow to decouple these sectors from carbon emissions. The number of power plants in the region should facilitate the build-up of synergies around the power sector, specially at Dąbrowa Górnicza – Jaworzno. It is relevant that several large-scale emitters are in adjacent industrial areas, and that many facilities are operated by the same companies, for instance Tauron and JSW Koks SA.

The volumes emitted per source are generally too large to consider a collection network that is not based on a network of CO_2 pipelines. However, railways are a ubiquitous infrastructure in Upper Silesia and almost all mapped facilities have a dedicate rail terminal, so that the possibility of utilising railways for collecting CO_2 in liquid phase from the smaller sources, could be a possibility.



There are carbon utilisations options already being implemented for synthetic fuels production, but the existing chemical sector also calls for studies on the possibility of further integration of CO_2 in the production chains.

The major difficulty for implementing an ICCUS network in Upper Silesia is the limited storage capacity, around 110 Mt, mostly at Tier 1 assessment. For CCUS to have a meaningful impact in reducing the emissions from the large sources in the region it probably requires scenarios of CO_2, either by trunk pipeline to other regions of Poland or along the Gliwice waterway canal to the Baltic, sea and then to offshore storage areas.

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Table 4-23 Upper Silesia cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	Higher concentration of sources (11) in the Dąbrowa Górnicza – Jaworzno – Katowice area. In southern Upper Silesia, dispersed sources.	+
	Emission volume distribution	The Dąbrowa Górnicza – Jaworzno concentrates 60% (18Mt/y) of the total emissions (30.4 Mt/y). Two sources in Rybnik and Laziska Gorne also very relevant (10 Mt/y).	+
	Emission volume profile	Mostly stable emissions, but emissions in the largest source (power plant at Rybnik) decreasing.	+
	Emissions type and quality	Almost exclusively coal combustion emissions, except for some process emissions in iron & steel plant. No high concentration sources.	~
AREA	Industrial area character	All sources are related to power plants, except for one iron&stell mill and a coke production plant. The chemical sector at Oswiecim is also relevant.	+
	Importance of industry	Upper Silesia is an important industrial area. Coal mining plays an important economical role.	+
	Cluster recognition	The RECOPOL project had previously identified the area as a cluster for CCS.	+
INDUSTRIES	Integration of industry	A small number of companies owns all mapped sources, with TAURON, JSW Koks SA, operating several facilities. There is proximity, or even continuity of industrial complexes owned by ARCEELLORMITTAL, TAMEH and TAURON.	+
	Decarbonisation alternatives	Fuel switch to biomass is the main alternative being considered. This could lead to interest in BECCS.	+
	CCU	CO_2 utilisation for methanation is being implemented, but there are also potential uses in the Oswiecim chemical sector	+
	Motivation for decarbonisation	National strategies for climate mitigation.	~
	Motivation for CCS	Coal is an important asset for the regional and national economy. CCUS can decouple the use of coal from CO_2 emissions.	+
INFRASTRUCTURE	CO_2 collection options	Railway connections to almost every major source, including operational terminals. A new CO_2 pipeline network can be considered.	+
	CO_2 consolidation options	All sources established in industrial polygons, no anticipated problems for finding space for CO_2 consolidation.	+
	Existing CO_2 infrastructure	No existing infrastructure. Pilot capture plant at Laziska Tauron power plant.	–
	Infrastructure reuse options	Not possible.	-
STORAGE	Storage accessibility	Distance to onshore sites in the order of 30 km to 60 km.	~
	Storage capacity	96 Mt in Deep saline aquifers (at Tier 1) and 11 Mt in uneconomic coal beds (at Tier 2). Insufficient when compared to current emissions of 30.4 Mt/y.	-
	Storage flexibility	Poor, given that there are only two storage units in DSA and that UCB are at a low maturity level for CO_2 injection.	-
	Storage development integration	No organisation has put forward plans for developing storage. Tauron is engaging in pilot capture projects and CO_2 utilisation.	-

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4.8 West Macedonia – Greece

4.8.1 Emissions and industry sectors

Five active CO_2 emission facilities were inventoried in the West Macedonia promising region, with second largest total emissions in STRATEGY CCUS, 20.4 Mt/y in 2017 (Table 4-24). Such a high emission rate results from four out of the five sources being coal (lignite) based power plants. The fifth installation is a quicklime and lime factory, emitting only 40 kt/y, irrelevant when put in the context of the total emissions in the region (Figure 4-49).

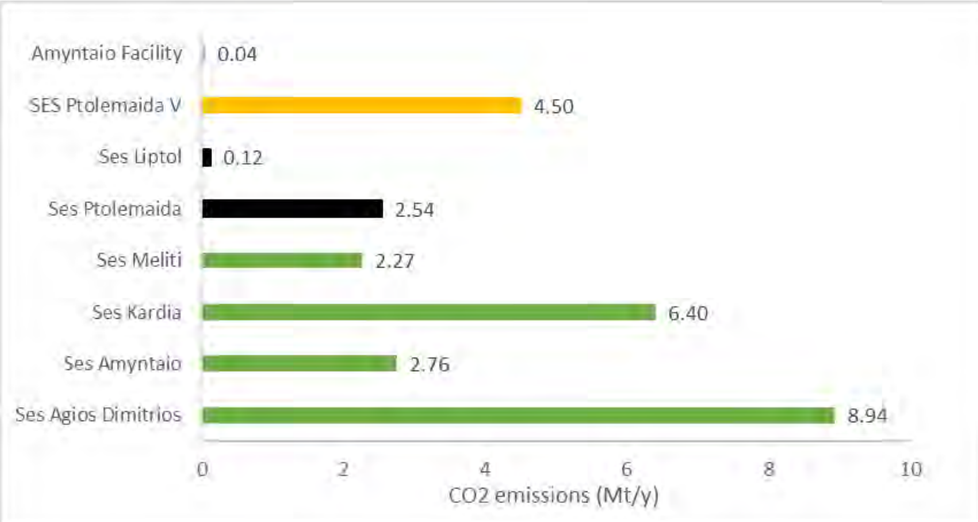

Figure 4-49 Emissions per facilities in West Macedonia. "Amyntaio Facility" is a quicklime and lime installation, all others are coal power plants. Green represents active sources, black sources closed in 2015 and yellow represents "SES Ptolomeaida V", a new coal power plant scheduled for start operating in 2022.

The current government, in line with the EU commission's Green Deal, has decided to shut down the four active power plants by the end of 2023 if not earlier, mirroring a decision for two other coal power plants that closed in 2015. Thus, the trend in CO_2 emissions is expected to decrease drastically in the 2020's and, ultimately (if the shutdown plans go forward) will be reduced to a new power plant that is under construction – the "SES Ptolemaida V" power plant (GR.ES.5). This new 660 MW power plant is scheduled to start operations in 2023, with estimated emissions of 4.5 Mt/y. "SES Ptolemaida V" was designed as a CCS-ready facility and it will run on lignite at least until 2028 after which switch to a different fuel should be completed (SADM, 2020).

Despite the planned shut-down for the four currently operational power plants, scenarios to be developed in STRATEGY CCUS should not discard the possibility that some sort of conversion of the facilities may be considered in the future, for instance with fuel switch to natural gas.

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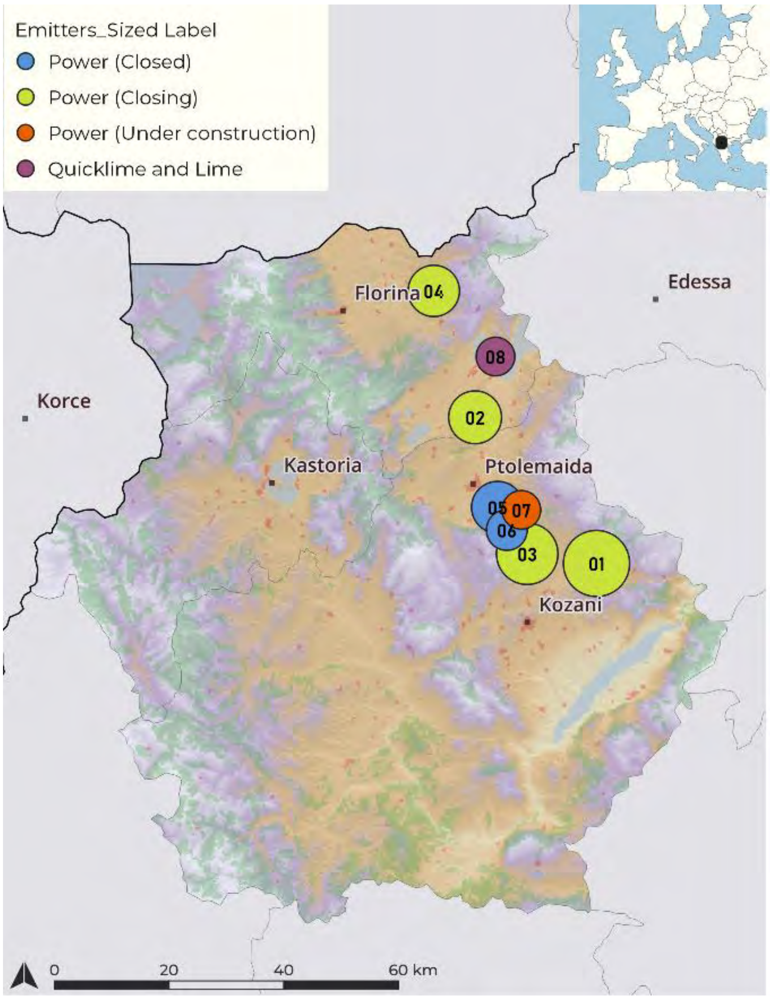

Figure 4-50 Locations of facilities with potential for CO_2 capture. Circle size is proportional to CO_2 emissions. Numbers refer to *Emitter ID* in Table 4-24. For detail see map in Appendix I.

Table 4-24 Main features of CO_2 emitting facilities in West Macedonia

Emitter ID	Facility name	Sector	City	Emissions (tCO_2/y)	Emission trend	Main fuel
GR.ES.1	Ses Agios Dimitrios	Power	Kozani	8940000	Falling	Coal (lignite)
GR.ES.2	Ses Amyntaio	Power	Amyntaio	2760000	Falling	Coal (lignite)
GR.ES.3	Ses Kardia	Power	Ptolemaida	6400000	Irregular	Coal (lignite)
GR.ES.4	Ses Meliti	Power	Florina	2270000	Irregular	Coal (lignite)
GR.ES.5	SES Ptolemaida	Power	Ptolemaida	2540000	Closed	Coal (lignite)
GR.ES.6	Ses Liptol	Power	Ptolemaida	118000	Closed	Coal (lignite)
GR.ES.7	SES Ptolemaida V	Power	Ptolemaida	4500000	Irregular	Coal (lignite)
GR.ES.8	Amyntaio facility	Quicklime & Lime	Amyntaio	40150	Stable	No data

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4.8.2 CO_2 Storage possibilities

The potential for CO_2 storage in West Macedonia is concentrated in onshore deep saline aquifers in the Mesohellenic Trough, a piggyback basin of 200 km length and 30-40 km width (Figure 4-50). The storage capacity is provided by two formations (Table 4-25):

i. the Pentalofo Formation, with Tsarnos and Kalloni daughter units, comprising conglomerates, turbiditic sandstones (occasionally coarse-grained) and shales, with a porosity ranging from 7% to 25% and an estimated theoretical storage capacity of 1277 Gt CO_2;
ii. the Eptachori Formation, mainly conglomerates, sandstones, marine turbiditic shales with lignitic horizon, marine sandstones and some pebbly conglomerates, with an average porosity of 15% and estimated theoretical storage capacity of 166 Mt CO_2.

Although the total theoretical storage capacity, above 1.4 Gt, is quite large, there are considerable gaps in data availability, and should be seen as a theoretical estimation, a first outcome of STRATEGY CCUS for the Greek case study. Therefore, this storage capacity qualifies as a low-level Tier 1 resource. The storage capacity will inevitably decrease as the assessments rise in Tier, but expectations are, due to the size of the Mesohellenic Trough, that West Macedonia will have more than enough storage capacity to accommodate the CO_2 to be produced at “SES Ptolemaida V”.

4.8.3 Spatial conditions for cluster and network development

Given the phase-out starting in 2023 of the four operating lignite power plants, the most relevant spatial condition for CCUS deployment in west Macedonia is the location of the “SES Ptolemaida V” CCS-ready power plant, scheduled to start operations in 2021 and with an expected lifetime of 30 years. Just like the power plants being shut-down, “SES Ptolemaida V” is located near the lignite mining district, about 40 km to 50 km from centre of the Mesohellenic Trough, where the storage capacity exists (Figure 4-51).

The topographic conditions between the source and the sedimentary basin are challenging, as the terrain is often steep, and altitude rises generally from the mining district to the potential storage locations, implying higher costs for laying pipeline and maintaining pressures. Transport by railway or waterways are not feasible given the volumes to be transported (4.5 Mt/y are expected to be produced at “SES Ptolemaida V”), nor is reutilisation of pipelines, since the nearest pipeline, the Trans Adriatic Pipeline (TAP), located at about 16 km from “SES Ptolemaida V”, is still being constructed and is designed to carry natural gas.

The best transport option seems to be a purposely built pipeline, probably following along a corridor defined by existing roadways, due to topographic constraints.

Scenarios to be built in STRATEGY CCUS should consider the possibility that some of the power plants scheduled to shut down may continue operating after 2028, either because decarbonisation alternatives are implemented (fuel switch to, natural gas, biomass or hydrogen, for instance) or because other utilisations are considered for the facilities. Even so, the transport conditions are not very different, as all these power plants are aligned along a N-S trend following the main roads in the area. Collection and consolidation of the CO_2 could be done with a pipeline following the same orientation.

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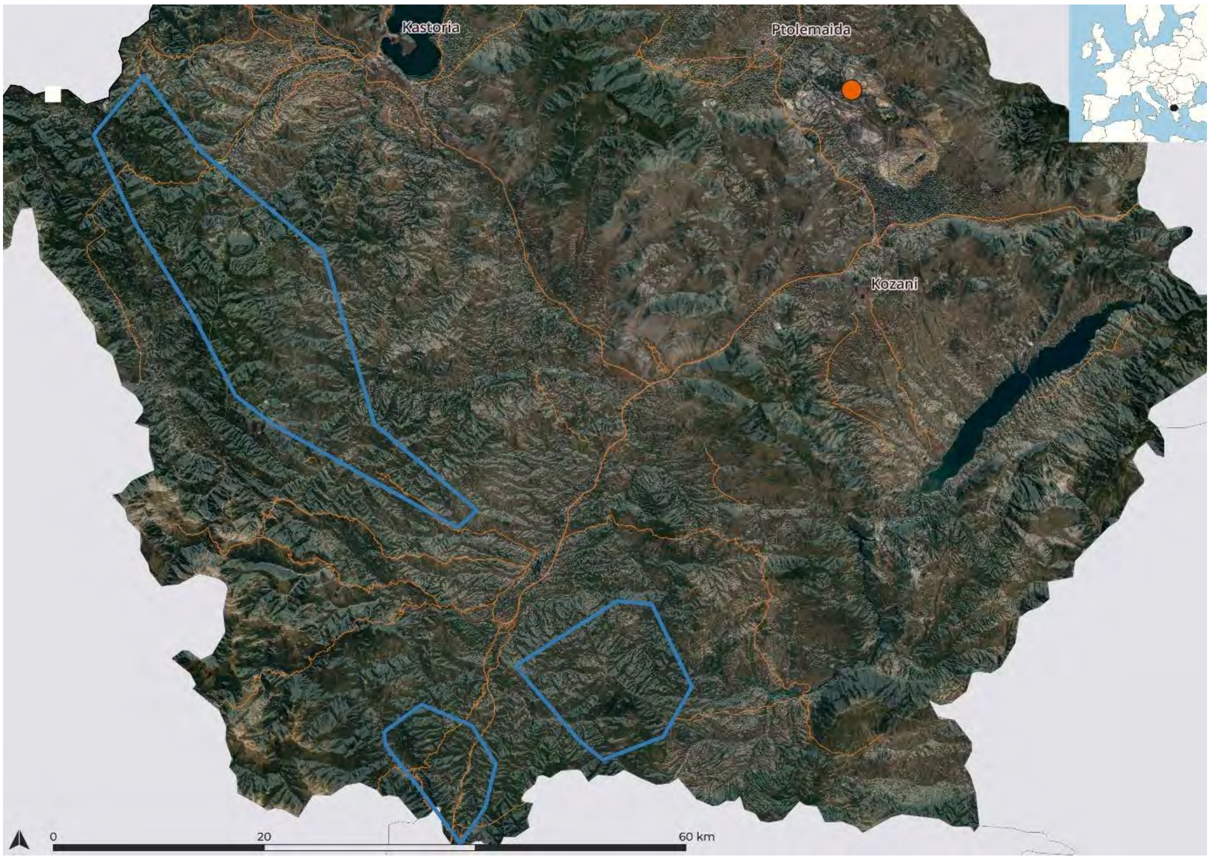

Figure 4-51 Topographic conditions between "SES Ptolemaida V" (red dot) and the storage units in the Mesohellenic Trough (blue polygons).

Table 4-25 Main features of potential storage units in West Macedonia

Storage Unit ID	Storage type	Storage_Unit	Formation	Lithology	Setting	Reservoir Depth (m)	Reservoir Thickness (m)	Storage capacity (Mt)
GR.SU.1	DSA	Mesohellenic Trough	Pentalofos	conglomerates, turbiditic sandstones (occassionally coarse-grained) and shales	Onshore	3500	2500	1277
GR.SU.2	DSA	Mesohellenic Trough	Eptachori	conglomerates, sandstones, marine turbiditic shales with lignitic horizon, marine sandstones and some pebbly conglomerates	Onshore	5000	1100	166

4.8.4 CO_2 utilisation options

There are no ongoing large-scale utilisations of CO_2 in West Macedonia, and the industrial and economic profile of the region does not lead to expectations that CO_2 uses could become a reality in the coming years. Still, in other regions of Greece there are perspectives for potential uses of CO_2 if the technologies are mature enough to be implemented with commercial aims.

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Integration of CO_2 into building materials, namely in aggregates, through mineral carbonation could be interesting application in the factories of Kebe, S.A., at Kilkis, in Central Macedonia, or in factories of Ravago Hellas BS and Novamix- Domochemical S.A., at Athens.

Conversion of the CO_2 into polymers (plastics, resins, foams) by the Crete Plastics S.A., Athens, or by the Elton international trading Company S.A., at Avlonas, are also possibilities to be considered, as is the production of synthetic fuels at the four refineries operated in Greece by Hellenic Petroleum S.A. and Motor Oil Hellas Corinth Refineries SA, all around Athens city.

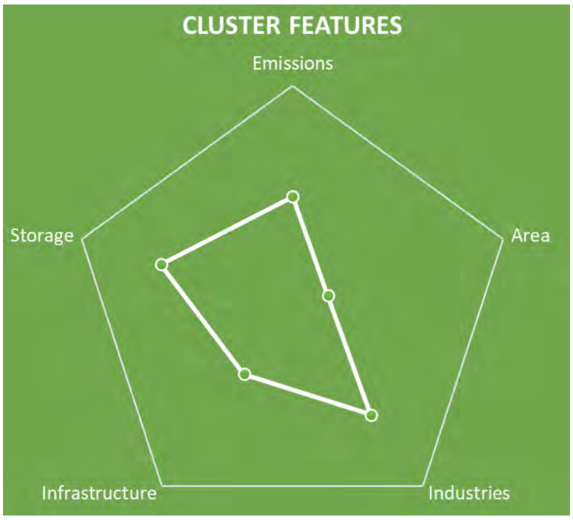
Direct uses of CO_2 for yield boosting, in greenhouses or in the manufacturing of urea and fertilisers, by the companies Megaplast S.A. and Hellenic Fertilizers and Chemicals Elfe S.A., respectively, has also been put forward.

None of these potential utilisations is yet taking place in Greece, but the utilisations and companies mentioned are considered to have the potential to use CO_2. In any case, large transport distances from the sources in Western Macedonia would be required, as most of the utilisations are near Athens, around 500 km south from the lignite mining district.

4.8.5 Main features of technical potential for ICCUS development

Perspectives for development of a CCUS integrated infrastructure encompassing multiple sources in West Macedonia are scant, since the main sources of emissions in the region, four lignite power plants, are being shut down in the period 2023-2028. All other industrial activity in the region is negligible in terms of CO_2 emissions.

This does not imply, however, that CCUS cannot become a reality in West Macedonia. It is possible that by the mid-2020' the new lignite "SES Ptolemaida V" power plant is the only relevant source in the region, with expected emissions of 4.5 Gt/y. This power plant was designed as CCS-ready, and therefore the possibility of deploying CO_2 capture was/is being considered. CCUS in West Macedonia may be feasibly at this location, with transport being made for storage in the Mesohellenic Trough and/or for utilisation in industries around Athens and Kilkis.



There is a high degree of uncertainty about the storage capacity in the Mesohellenic Trough, due to very limited information about deep geological conditions. Improving the storage capacity assessments is a priority, even if CO_2 capture is to be done at a single power plant, as the existing data about the storage complex does not allow for general planning on storage locations.

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Table 4-26 West Macedonia cluster features

GROUP	Feature/ factor	Comment for cluster	Significance +,~,–
EMISSIONS	Emission location distribution	One well identified locus: the lignite mining district along in which several power plants are operational (but due to shut down until 2028)	+
	Emission volume distribution	Operational point sources are four coal power plants with high emissions, and quicklime / lime producing factory with very small emissions. A new lignite power plant is to start operations in 2021 and it is considered CCS-ready.	~
	Emission volume profile	The operational power plants are scheduled to shut down from 2023 to 2028, and the only remaining large source will be the new "SES Ptolemaida V" lignite power plant, with expected emissions of around 4.5 Mt/y.	-
	Emissions type and quality	The emissions from the new power plant will be resulting from lignite combustion until 2028, after which fuel switch will be completed. The "SES Ptolemaida V" is said to be CCS-ready	~
AREA	Industrial area character	All industrial activity is based on lignite mining and operational power plants, including the quicklime and lime factory.	-
	Importance of industry	Government is planning phase out of the lignite until 2028, so that the industrial activity in the region may will decrease.	-
	Cluster recognition	No previous identification as a possible cluster for CCUS.	~
INDUSTRIES	Integration of industry	Power plants are well integrated with the mining activity, but both will be phased out.	~
	Decarbonisation alternatives	If the power plants do not shut down until 2028, possible decarbonisation alternatives would be fuel switch to biomass, creating the possibility for BECCS, or fuel switch to hydrogen.	+
	CCU	Currently no utilisations being made in West Macedonia, and the industrial profile of the region does not create expectations for it. Potential utilisations could occur in other regions of Greece, namely around Athens, for synthetic fuels production, aggregates for construction and polymers. Also, some interest in direct use in greenhouses and urea and fertilizer production	~
	Motivation for decarbonisation	National strategies for climate change mitigation	~
	Motivation for CCS	West Macedonia is a lignite producer and adopting CCUS can sustain continuation of mining activity.	~
INFRASTRUCTURE	CO_2 collection options	Rugged and hill terrain, without railways and waterways transport possibility, or possibility to reutilise pipelines. New pipeline seems to be the option	~
	CO_2 consolidation options	Since only one source may exist in the future, no need for CO_2 consolidation from multiple sources.	+
	Existing CO_2 infrastructure	No existing infrastructure.	–
	Infrastructure reuse options	No possibility to reuse existing pipelines, as these are not going towards the storage areas and will continue running natural gas.	-
STORAGE	Storage accessibility	Potential storage sites around 40-50 km away, through mountainous terrain.	~
	Storage capacity	Potentially high, estimated in more than 1Gt, but still at a very low level of assessment. High uncertainty.	+
	Storage flexibility	Unknown, given the low level of assessment.	-
	Storage development integration	PPC S.A., the owners of the new power plant, considered CCS as an option, since the "SES Ptolemaida V" is CCS-ready.	+

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5 Conclusions

The STRATEGY CCUS promising regions compose a portfolio of highly diversified cases for building Industrial CCUS clusters, illustrating that deploying the technology in different contexts requires a case to case approach that takes in to account technical requirements that vary for each promising region at the onset of the ICCUS implementation.

Identifying the strengths and weaknesses of each region could be done by analysing the five groups of technical features used to describe the potential for developing ICCUS clusters, i.e., i) emissions; ii) area; iii) industry; iv) infrastructures and v) storage.

For instance, it is noticeable that the Ebro Basin, in Spain, seems to present the most complete set of conditions to deploy the technology, with a diversified industrial sector, in which emission sources are concentrated in a few hotspots of facilities, and with a level of industry integration that seems to be aware and motivated to engage in ICCUS. But still, it has some weaknesses in that the storage capacity (assessed only onshore), may not be the adequate for the full potential of the technology to be attained in the region. With progress in storage resource maturity, there may be a need to look for other storage sites, outside the Ebro basin, possibly offshore.

Other regions present also very good conditions for building clusters. It could even be argued that the configuration and diversity of the industrial sources in the Rhone Valley is ideal for defining a network of capture and transport of CO_2. There is even the potential for relevant CO_2 utilisation in the chemical sector, for synthetic fuels and for mineral carbonation, again benefitting from the highly diversified industrial fabric. However, there is just not enough storage capacity to accommodate all the storage capacity needs required if ICCUS is to have an impact in the region. This is, therefore, a scenario in which transport to other regions, perhaps from the Marseille-Fos port, needs to be considered, together with a maximisation of the potential for CO_2 utilisation.

CO_2 utilisation can, in fact, be a major solution for some of the regions in STRATEGY CCUS, at least in the early stages of CCUS deployment. Not surprisingly it is CO_2-EOR that should provide the first large scale opportunity, with CO_2 being a commodity that provides the incentive for implementing CO_2 capture and transport. Northern Croatia, in particular, but also the Galati Region in Romania, are well suited to engage in utilising CO_2 for EOR, a practice that already is ongoing in Croatia, but that can be further expanded.

Neither the Galati Region or Northern Croatia present very strong cases in terms of the current emissions or clustering of the reduced number of existing sources, but both have a good storage potential in well studied depleted hydrocarbons fields, either abandoned or still under production. CO_2-EOR can not only benefit the economy in those regions, by improving oil production, but would also allow to gain the experience and incentive to continue CO_2 storage in the hydrocarbon fields once they are abandoned, benefitting from the infrastructure that exists or would be built for CO_2-EOR. Scenarios need to take into account the volume of CO_2 avoided, as not only hydrocarbons are produced, but also a fraction of the injected CO_2 will after some time also be produced in the wells (implying perhaps the need to separate it from the produced fluid and reinjected).

But CO_2-EOR is not the only large-scale utilisation that can be conceived in the STRATEGY CCUS regions, and the Portuguese Strategy for Hydrogen relies in the ability to capture large volumes of

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CO_2 to induce methanation and other chemical processes to produce synthetic natural gas and other synthetic fuels (such as aviation fuels). The scenarios in the Lusitanian Basin need to consider these CO_2 utilisation needs. That solution will not be enough to meet all the CO_2 capture requirements in the region, especially those coming from the process emissions in the cement industry. Fortunately, the spatial arrangement of the sources and the estimated storage capacity, onshore and offshore, are adequate for building a promising case for ICCUS development in the Lusitanian Basin.

Other regions are more monolithic in their industrial structure, with coal power plants being almost the sole responsible for the large CO_2 emissions in the West Macedonia, in Greece, and Upper Silesia, in Poland. In those cases, the national strategies impose different scenarios for those two coal mining regions. In Greece, a phase-out of coal power plants has been decided, and one single coal power plant is expected to be running by 2028. Still under construction, the power plant is CCS-ready. A decision to engage in a CCUS project could become of social relevance to maintain jobs in the coal mining activity in the region. The conditions for storage are still at a poor level of maturity, but the initial assessments points towards good storage conditions in the Mesohellenic Through.

There does not seem to be a phasing out of coal in Upper Silesia, where coal mining is a very important economic activity, and implementing ICCUS can be instrumental in decoupling it from the CO_2 emissions in the coal power plants. The technical context is certainly very good, with the emissions volumes, distribution of sources and interaction of industry being very favourable for deploying ICCUS in the region. The storage conditions are, nonetheless, far from ideal and it is very likely that scenarios for this region need to consider long distance transport to other storage opportunities in Poland or neighbouring countries.

The Paris basin case is very specific in that it is not and highly industrialised region, nor does it have large point sources, but it has a considerable number of Energy-From-Waste power plants that can provide an opportunity to implement ICCUS projects with negative emissions. Together with the already existing experience on utilisation of CO_2 in greenhouses, developing ICCUS in the Paris Basin would benefit from very good storage potential in depleted hydrocarbon fields, able to provide safe conditions for storage while requiring less investments for increasing the maturity of the storage sites.

Maturity of the storage resource assessments is, perhaps, the biggest challenges for a detailed planning for implementing ICCUS networks in the STRATEGY CCUS regions. Overall, and as described in Deliverable D2.3, maturity of the resource assessments is low, being almost all at Tier 1 and seldom reaching Tier 2 for deep saline aquifers. The saline aquifer assessments in Northern Croatia, Galati Region, West Macedonia, Upper Silesia, Rhone Valley and offshore Portugal, are at Tier 1 and uncertainty is very high. Only in the Paris Basin, Ebro Basin and onshore Portugal, is uncertainty lower, but still maturity is only at Tier 2. Depleted hydrocarbon fields in the Paris Basin, Northern Croatia and Galati Region provide, by definition, the only prospects and should be the primary targets in those regions.

Raising the maturity level of the resources assessments is crucial for the detailed planning of the ICCUS development in the STRATEGY CCUS regions and the uncertainty that still prevails in the storage capacity needs to be take into account in the scenarios to be developed.

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Appendix I. Maps of emitters, storage locations and transport features

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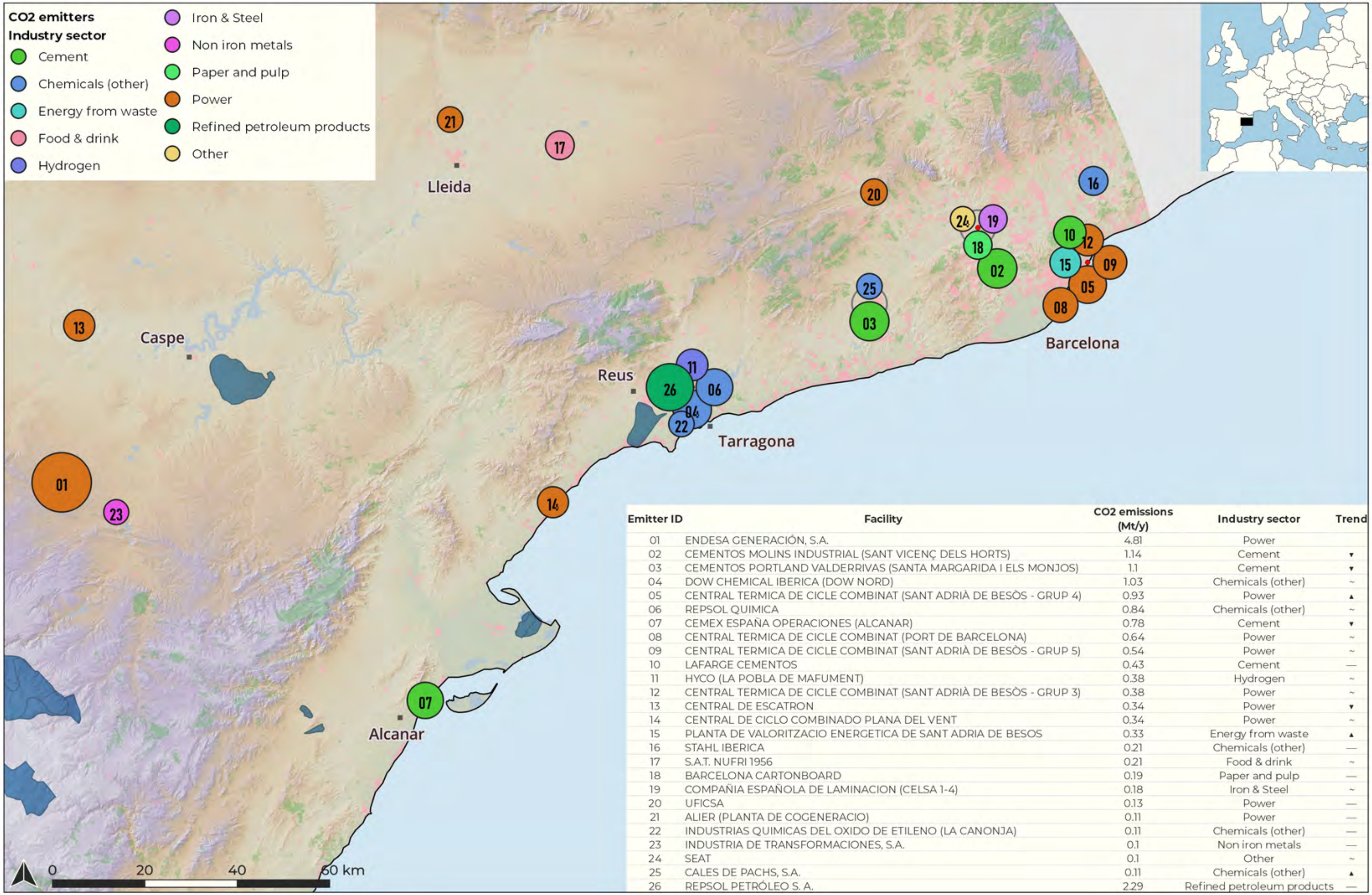
Maps of Ebro Basin

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 837754

Ebro basin | Emitters



Emitter ID	Facility	CO2 emissions (Mt/y)	Industry sector	Trend
01	ENDESA GENERACIÓN, S.A.	4.81	Power	
02	CEMENTOS MOLINS INDUSTRIAL (SANT VICENÇ DELS HORTS)	1.14	Cement	▼
03	CEMENTOS PORTLAND VALDERRIVAS (SANTA MARGARIDA I ELS MONJOS)	1.1	Cement	▼
04	DOW CHEMICAL IBERICA (DOW NORD)	1.03	Chemicals (other)	~
05	CENTRAL TERMICA DE CICLE COMBINAT (SANT ADRIÀ DE BESÒS - GRUP 4)	0.93	Power	▲
06	REPSOL QUIMICA	0.84	Chemicals (other)	~
07	CEMEX ESPAÑA OPERACIONES (ALCANAR)	0.78	Cement	▼
08	CENTRAL TERMICA DE CICLE COMBINAT (PORT DE BARCELONA)	0.64	Power	~
09	CENTRAL TERMICA DE CICLE COMBINAT (SANT ADRIÀ DE BESÒS - GRUP 5)	0.54	Power	~
10	LAFARGE CEMENTOS	0.43	Cement	—
11	HYCO (LA POBLA DE MAFUMENT)	0.38	Hydrogen	~
12	CENTRAL TERMICA DE CICLE COMBINAT (SANT ADRIÀ DE BESÒS - GRUP 3)	0.38	Power	~
13	CENTRAL DE ESCATRON	0.34	Power	▼
14	CENTRAL DE CICLO COMBINADO PLANA DEL VENT	0.34	Power	~
15	PLANTA DE VALORITZACIO ENERGETICA DE SANT ADRIA DE BESOS	0.33	Energy from waste	▲
16	STAHL IBERICA	0.21	Chemicals (other)	—
17	S.A.T. NUFRI 1956	0.21	Food & drink	~
18	BARCELONA CARTONBOARD	0.19	Paper and pulp	—
19	COMPAÑIA ESPAÑOLA DE LAMINACION (CELSA 1-4)	0.18	Iron & Steel	~
20	UFICSA	0.13	Power	—
21	ALIER (PLANTA DE COGENERACIO)	0.11	Power	—
22	INDUSTRIAS QUIMICAS DEL OXIDO DE ETILENO (LA CANONJA)	0.11	Chemicals (other)	—
23	INDUSTRIA DE TRANSFORMACIONES, S.A.	0.1	Non iron metals	—
24	SEAT	0.1	Other	~
25	CALES DE PACHS, S.A.	0.11	Chemicals (other)	▲
26	REPSOL PETRÓLEO S. A.	2.29	Refined petroleum products	—

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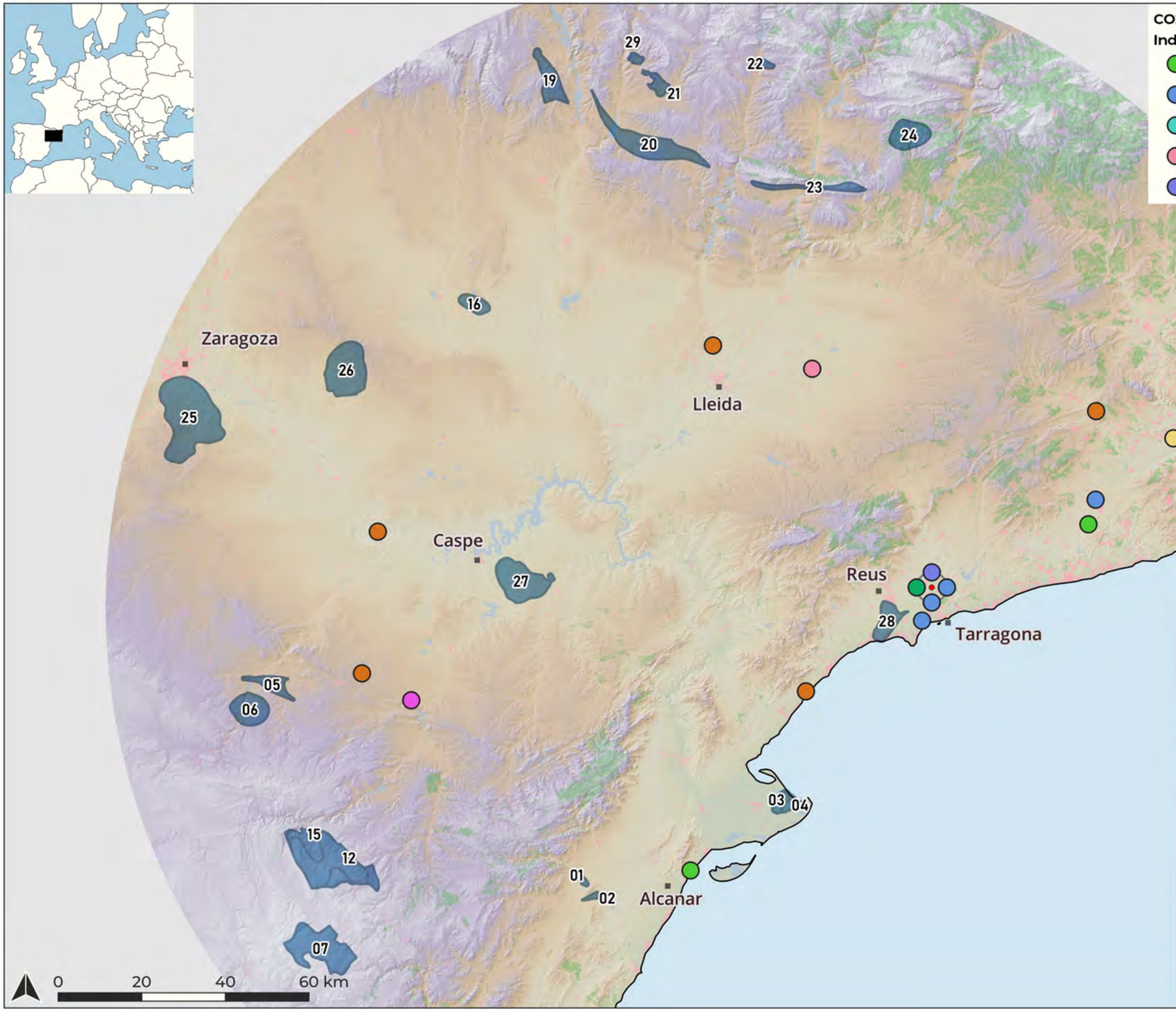
Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Ebro basin | Storage units

STRATEGY CCUS



Storage unit ID	Name	Storage capacity (Mt CO2)	Type
01	Salsadella	2.52	DSA
02	Salsadella	3.05	DSA
03	Delta del Ebro	4.88	DSA
04	Delta del Ebro	1.13	DSA
05	Obón-Oliete	5.69	DSA
06	Obón-Oliete	6.32	DSA
07	Maestrazgo	12.76	DSA
12	Maestrazgo	21.82	DSA
15	Maestrazgo	103.43	DSA
16	Sariñena	2.12	DSA
19	Olsón	4.15	DSA
20	Benabarre	2.67	DSA
21	Santa Creu-Graus	2.68	DSA
22	Tamurcia	0.11	DSA
23	Sierras Marginales	0.92	DSA
24	Isona	0.95	DSA
25	Lopin	29.01	DSA
26	Monegrillo	24.84	DSA
27	Caspe Mayals	41.99	DSA
28	Reus	21.03	DSA
29	Centenera	6.80	DSA

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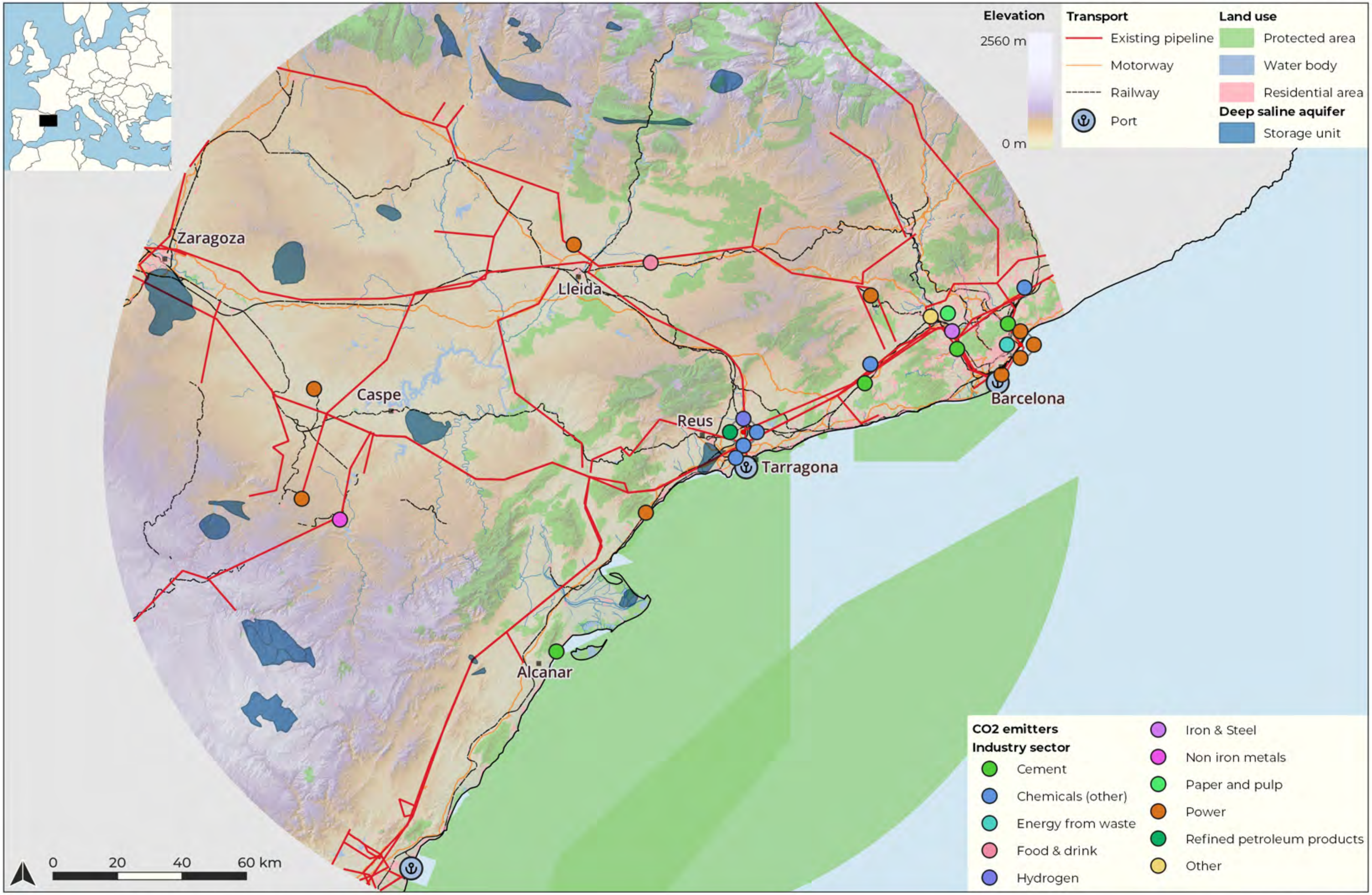
Ebro basin | Transport options



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Web Mercator projection (EPSG 3857)
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Maps of Galati Region

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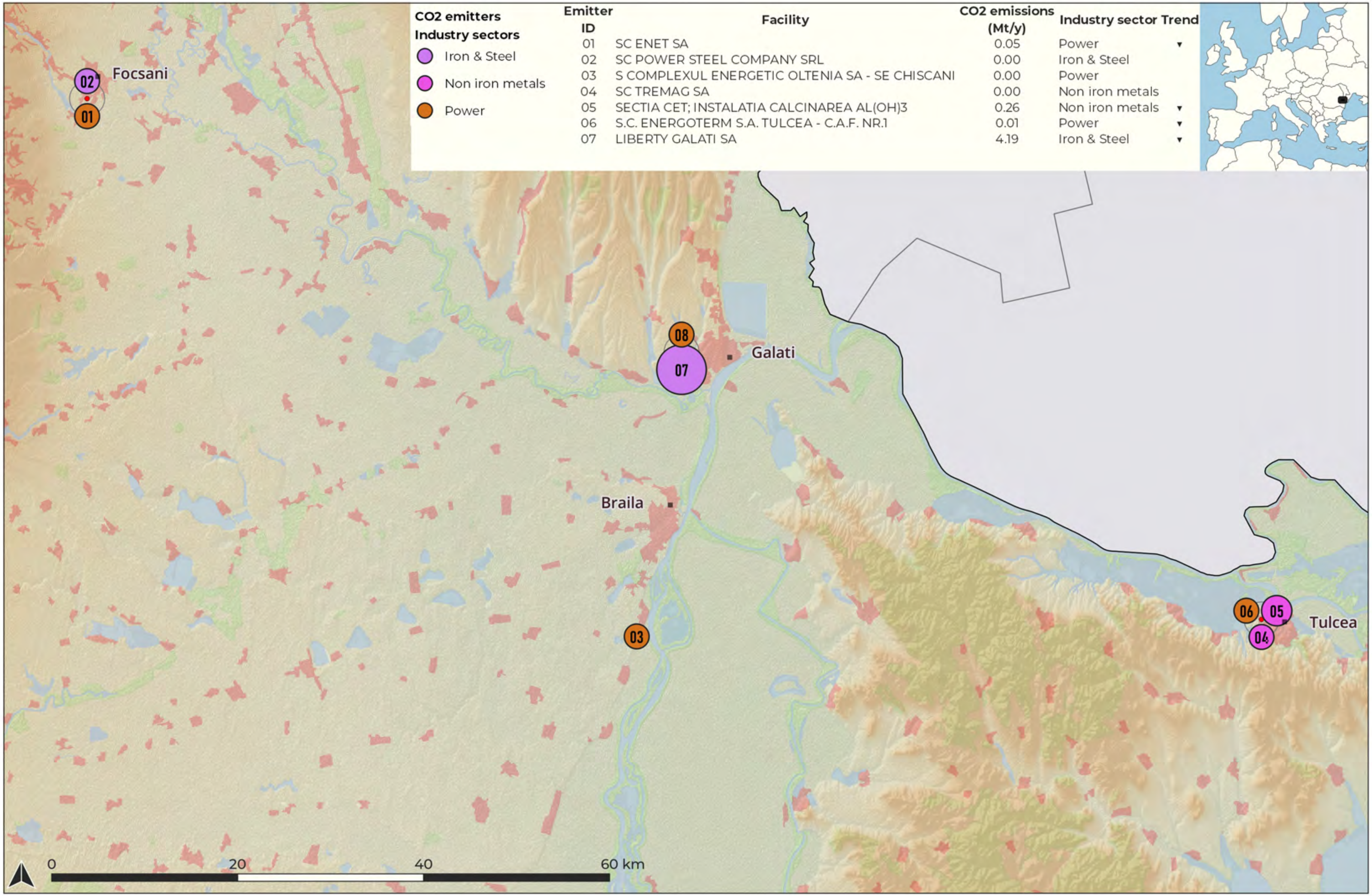
Galati area | Emitters



Emitter ID	Facility	CO2 emissions (Mt/y)	Industry sector	Trend
01	SC ENET SA	0.05	Power	▼
02	SC POWER STEEL COMPANY SRL	0.00	Iron & Steel	
03	S COMPLEXUL ENERGETIC OLTENIA SA - SE CHISCANI	0.00	Power	
04	SC TREMAG SA	0.00	Non iron metals	
05	SECTIA CET; INSTALATIA CALCINAREA AL(OH)3	0.26	Non iron metals	▼
06	S.C. ENERGOTERM S.A. TULCEA - C.A.F. NR.1	0.01	Power	▼
07	LIBERTY GALATI SA	4.19	Iron & Steel	▼

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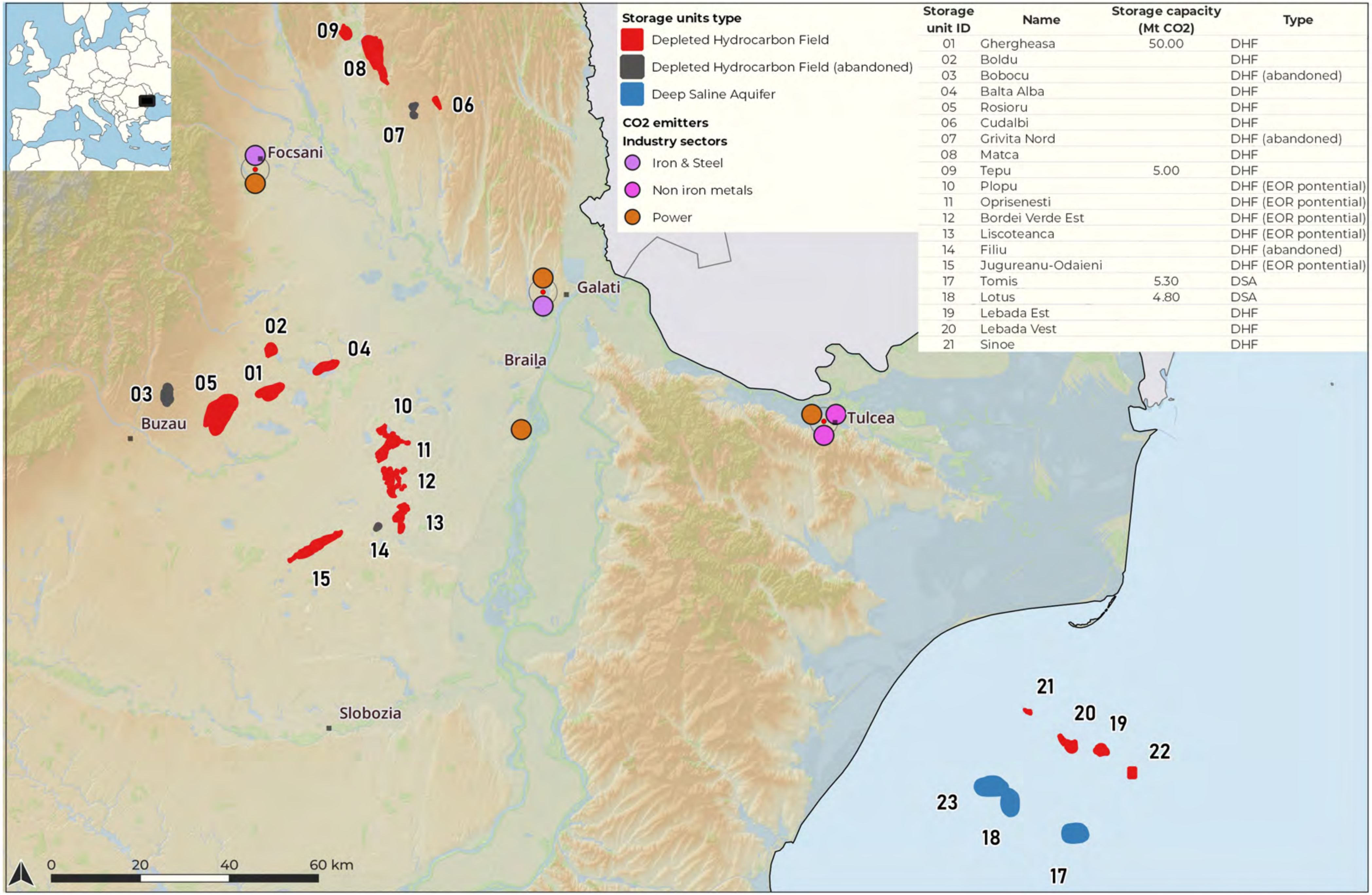
Galati area | Storage units



Storage unit ID	Name	Storage capacity (Mt CO2)	Type
01	Ghergheasa	50.00	DHF
02	Boldu		DHF
03	Bobocu		DHF (abandoned)
04	Balta Alba		DHF
05	Rosioru		DHF
06	Cudalbi		DHF
07	Grivita Nord		DHF (abandoned)
08	Matca		DHF
09	Tepu	5.00	DHF
10	Plopu		DHF (EOR pontential)
11	Oprisenesti		DHF (EOR pontential)
12	Bordei Verde Est		DHF (EOR pontential)
13	Liscoteanca		DHF (EOR pontential)
14	Filiu		DHF (abandoned)
15	Jugureanu-Odaieni		DHF (EOR pontential)
17	Tomis	5.30	DSA
18	Lotus	4.80	DSA
19	Lebada Est		DHF
20	Lebada Vest		DHF
21	Sinoe		DHF

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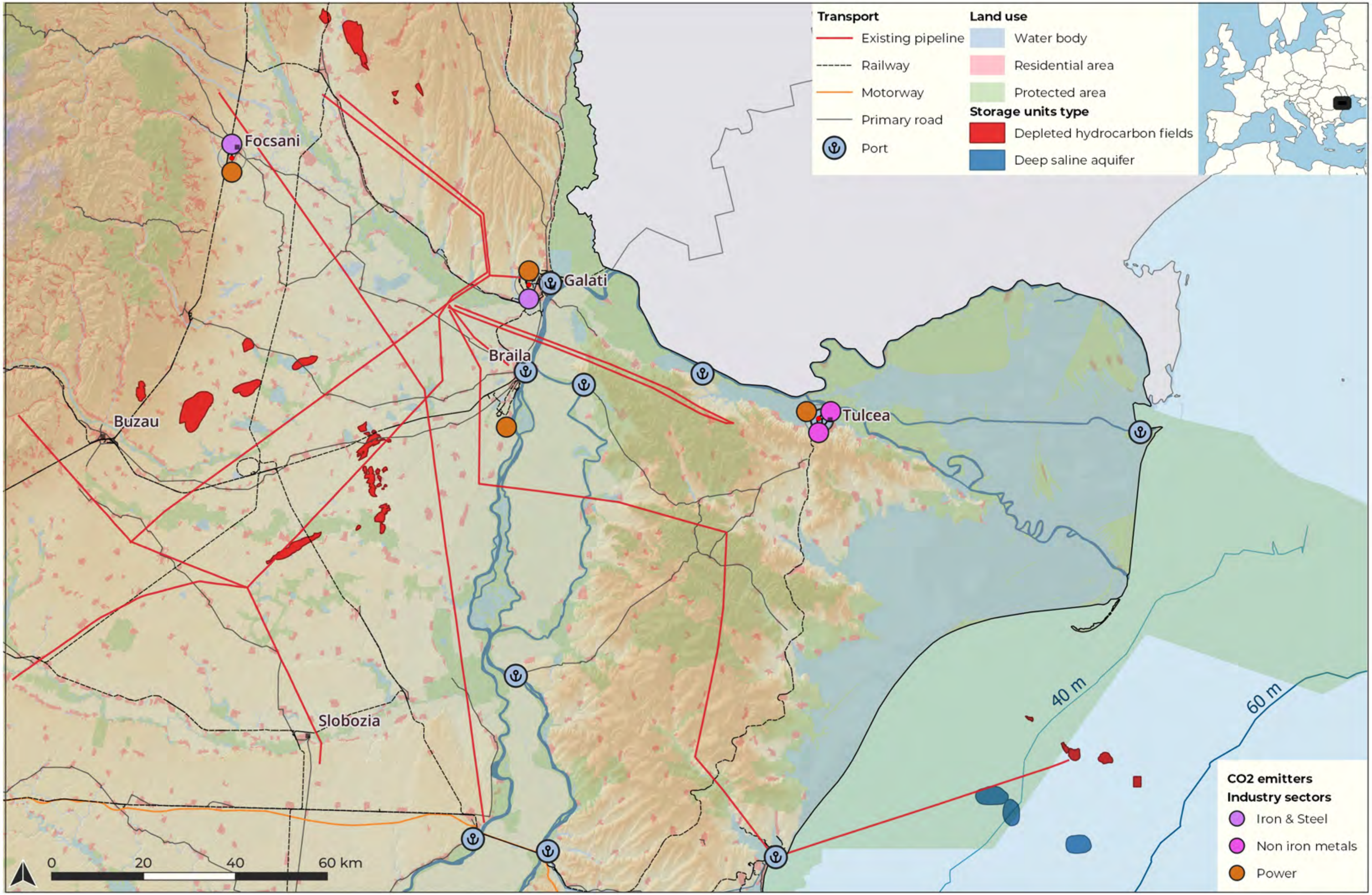
Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Galati area | Transport options

STRATEGY CCUS



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Web Mercator projection (EPSG 3857)
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Maps of Lusitanian Basin

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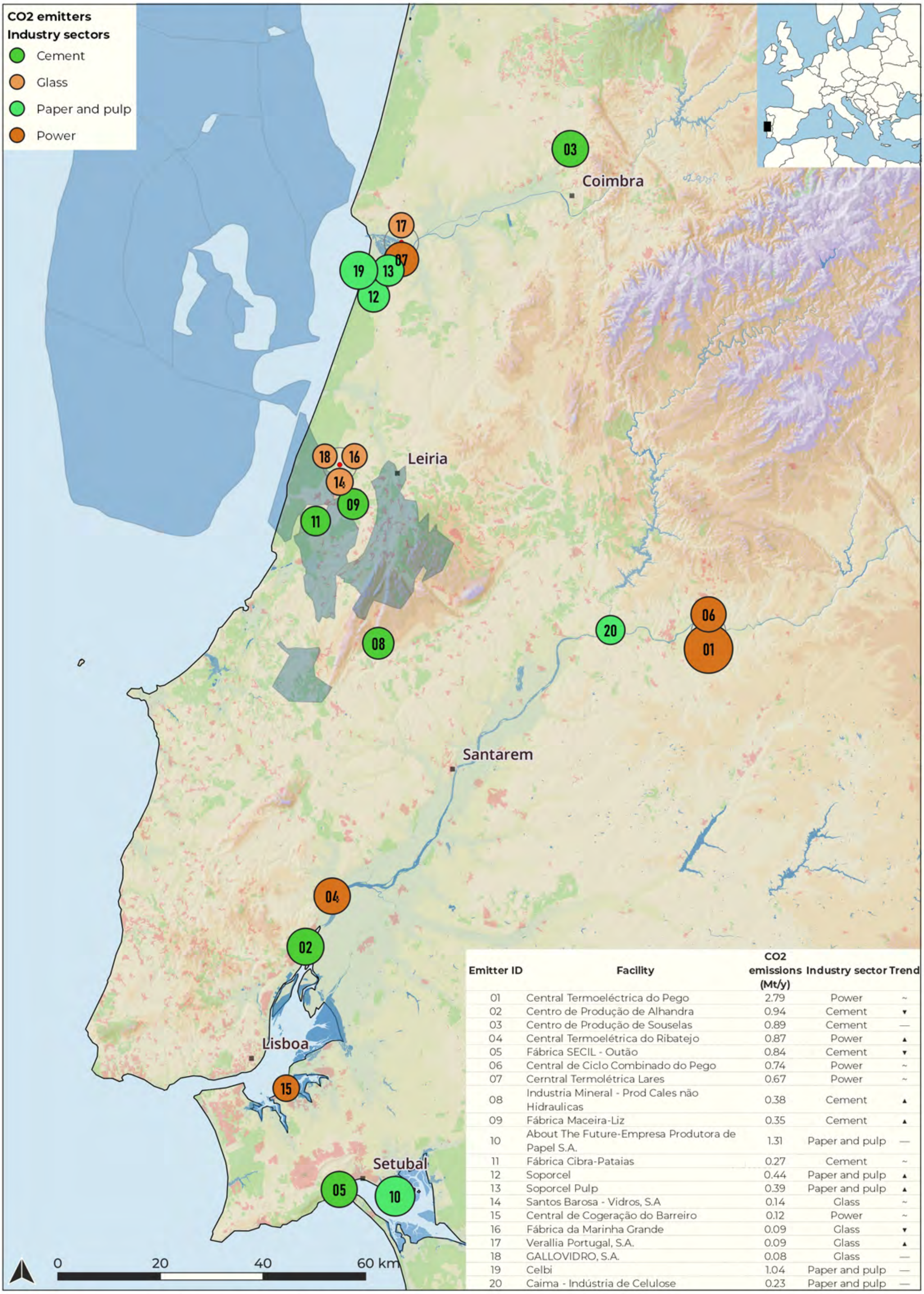
Lusitanian basin | Emitters

STRATEGY CCUS



Emitter ID	Facility	CO2 emissions (Mt/y)	Industry sector	Trend
01	Central Termoeléctrica do Pego	2.79	Power	~
02	Centro de Produção de Alhandra	0.94	Cement	▼
03	Centro de Produção de Souselas	0.89	Cement	—
04	Central Termoelétrica do Ribatejo	0.87	Power	▲
05	Fábrica SECIL - Outão	0.84	Cement	▼
06	Central de Ciclo Combinado do Pego	0.74	Power	~
07	Cerntral Termolétrica Lares	0.67	Power	~
08	Industria Mineral - Prod Cales não Hidraulicas	0.38	Cement	▲
09	Fábrica Maceira-Liz	0.35	Cement	▲
10	About The Future-Empresa Produtora de Papel S.A.	1.31	Paper and pulp	—
11	Fábrica Cibra-Pataias	0.27	Cement	~
12	Soporcel	0.44	Paper and pulp	▲
13	Soporcel Pulp	0.39	Paper and pulp	▲
14	Santos Barosa - Vidros, S.A	0.14	Glass	~
15	Central de Cogeração do Barreiro	0.12	Power	~
16	Fábrica da Marinha Grande	0.09	Glass	▼
17	Verallia Portugal, S.A.	0.09	Glass	▲
18	GALLOVIDRO, S.A.	0.08	Glass	—
19	Celbi	1.04	Paper and pulp	—
20	Caima - Indústria de Celulose	0.23	Paper and pulp	—

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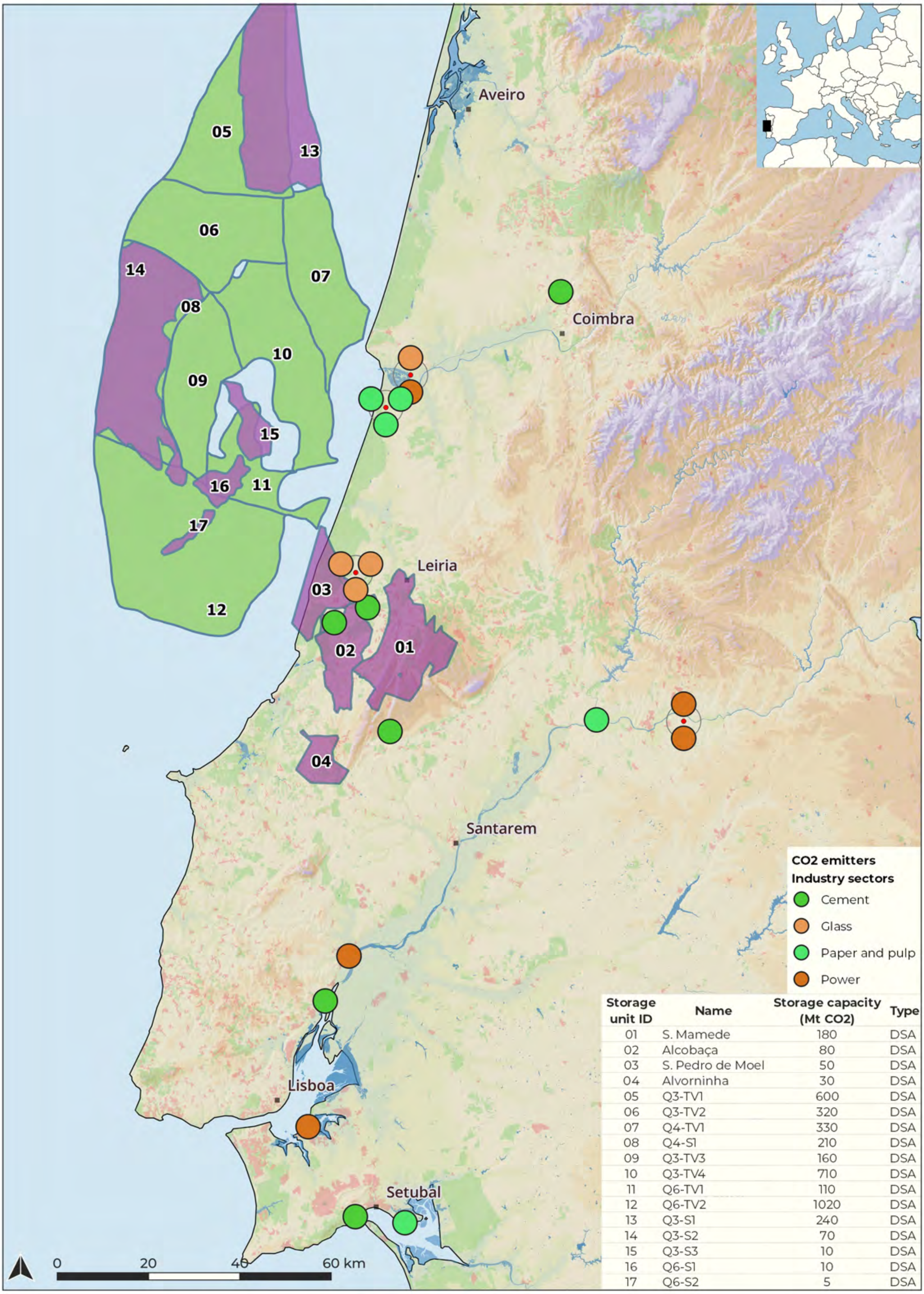
Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Lusitanian basin | Storage units



Storage unit ID	Name	Storage capacity (Mt CO2)	Type
01	S. Mamede	180	DSA
02	Alcobaça	80	DSA
03	S. Pedro de Moel	50	DSA
04	Alvorninha	30	DSA
05	Q3-TV1	600	DSA
06	Q3-TV2	320	DSA
07	Q4-TV1	330	DSA
08	Q4-S1	210	DSA
09	Q3-TV3	160	DSA
10	Q3-TV4	710	DSA
11	Q6-TV1	110	DSA
12	Q6-TV2	1020	DSA
13	Q3-S1	240	DSA
14	Q3-S2	70	DSA
15	Q3-S3	10	DSA
16	Q6-S1	10	DSA
17	Q6-S2	5	DSA

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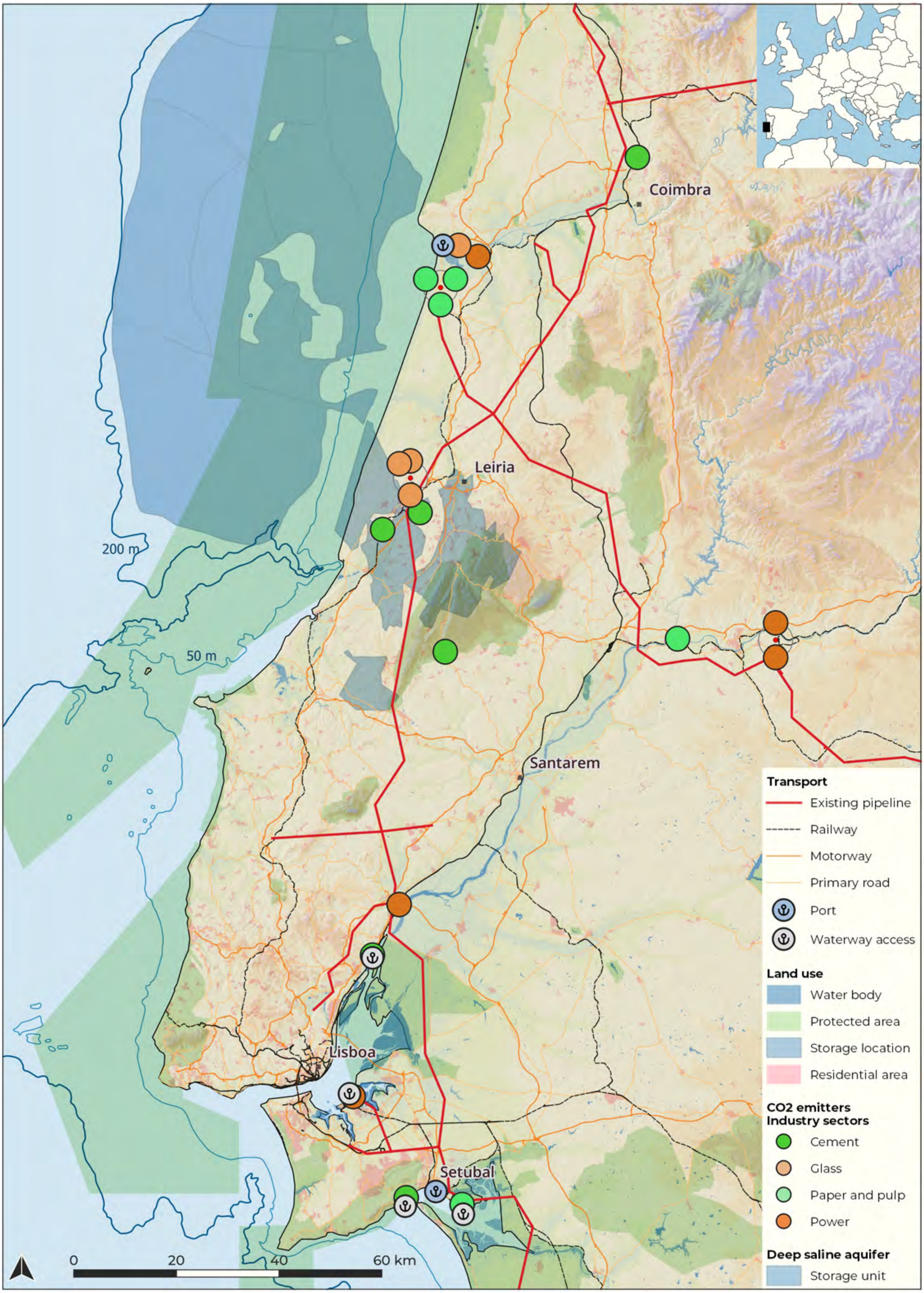
Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Lusitanian basin | Transport options

STRATEGY CCUS



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Web Mercator projection (EPSG 3857).
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Maps of Northern Croatia

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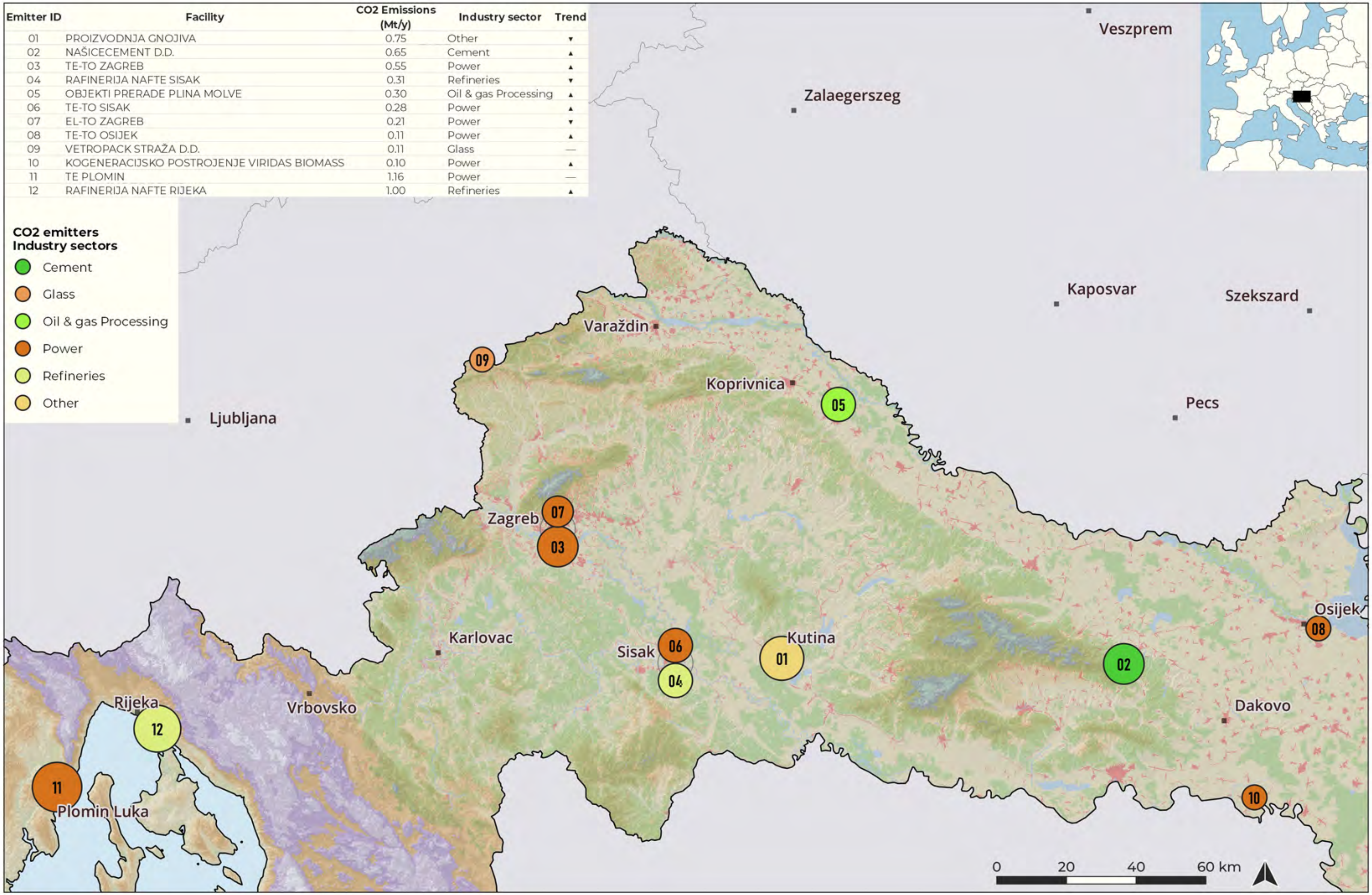
Northern Croatia | Emitters

Emitter ID	Facility	CO2 Emissions (Mt/y)	Industry sector	Trend
01	PROIZVODNJA GNOJIVA	0.75	Other	▼
02	NAŠICECEMENT D.D.	0.65	Cement	▲
03	TE-TO ZAGREB	0.55	Power	▲
04	RAFINERIJA NAFTE SISAK	0.31	Refineries	▼
05	OBJEKTI PRERADE PLINA MOLVE	0.30	Oil & gas Processing	▲
06	TE-TO SISAK	0.28	Power	▲
07	EL-TO ZAGREB	0.21	Power	▼
08	TE-TO OSIJEK	0.11	Power	▲
09	VETROPACK STRAŽA D.D.	0.11	Glass	—
10	KOGENERACIJSKO POSTROJENJE VIRIDAS BIOMASS	0.10	Power	▲
11	TE PLOMIN	1.16	Power	—
12	RAFINERIJA NAFTE RIJEKA	1.00	Refineries	▲



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Web Mercator projection (EPSG 3857)
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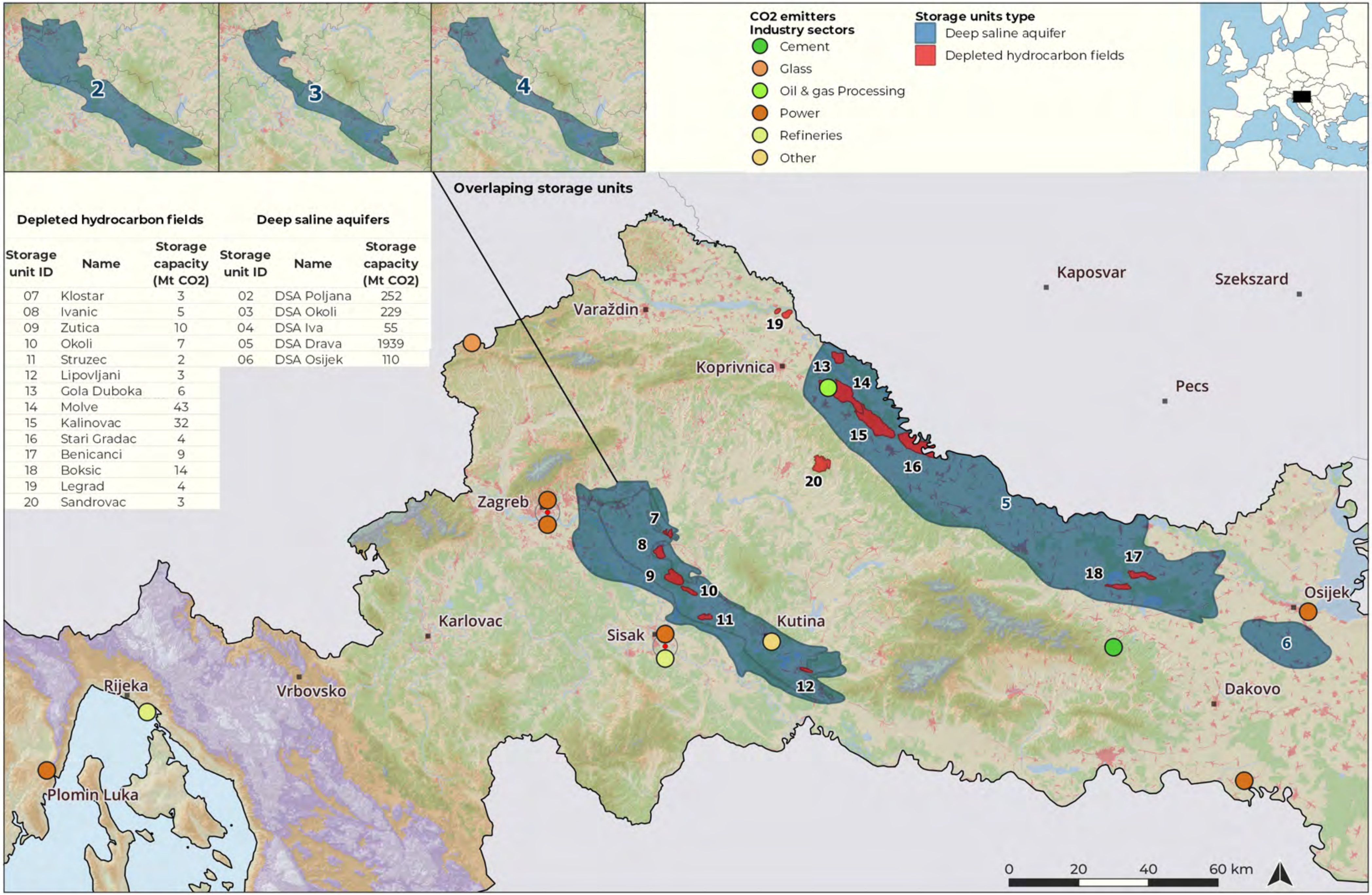
Northern Croatia | Storage units



Depleted hydrocarbon fields

Storage unit ID	Name	Storage capacity (Mt CO2)
07	Klostar	3
08	Ivanic	5
09	Zutica	10
10	Okoli	7
11	Struzec	2
12	Lipovljani	3
13	Gola Duboka	6
14	Molve	43
15	Kalinovac	32
16	Stari Gradac	4
17	Benicanci	9
18	Boksic	14
19	Legrad	4
20	Sandrovac	3

Deep saline aquifers

Storage unit ID	Name	Storage capacity (Mt CO2)
02	DSA Poljana	252
03	DSA Okoli	229
04	DSA Iva	55
05	DSA Drava	1939
06	DSA Osijek	110

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Web Mercator projection (EPSG 3857)
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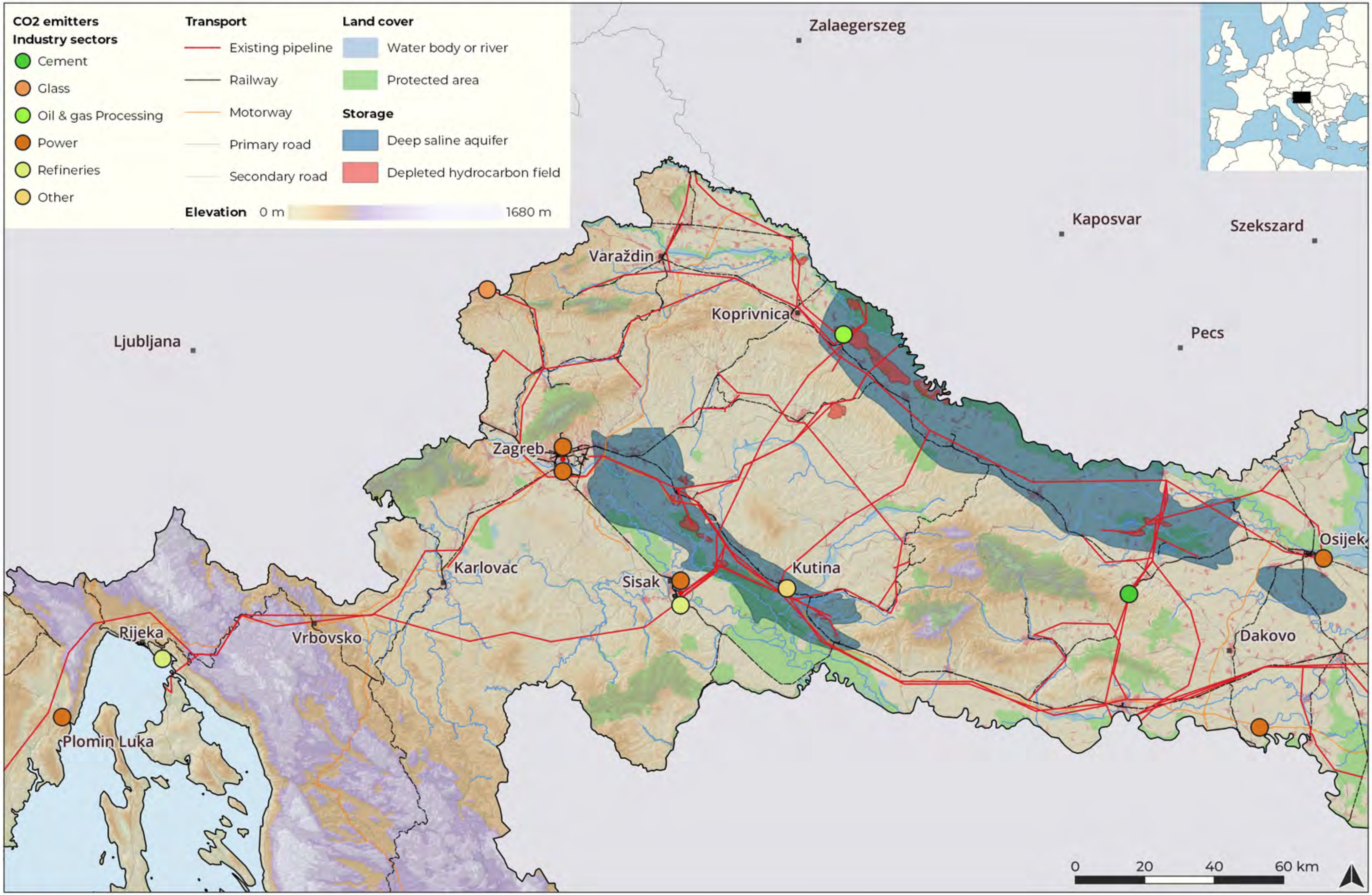
Northern Croatia | Transport options



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Web Mercator projection (EPSG 3857)
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Maps of Paris Basin

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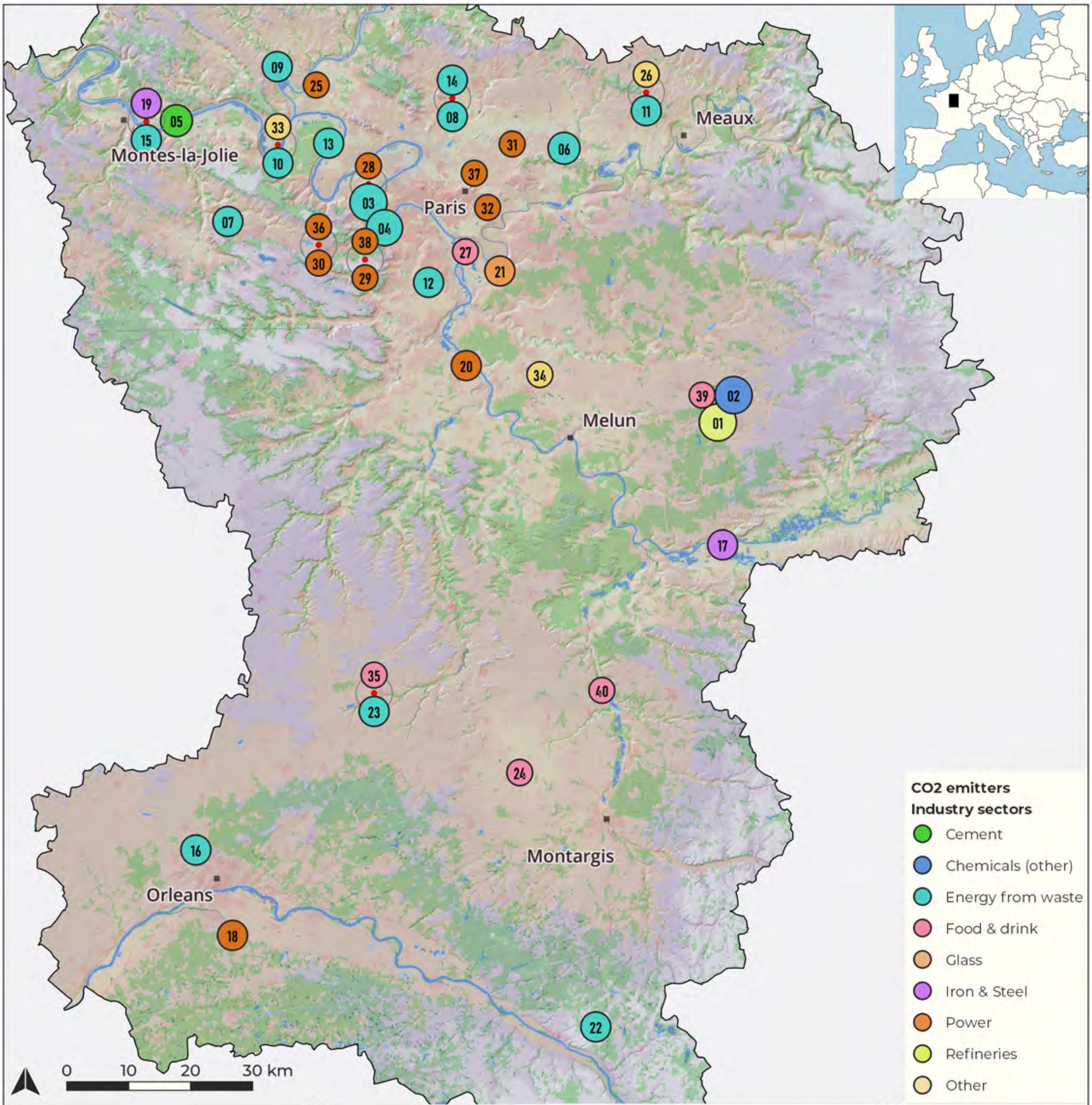
Paris basin | Emitters

STRATEGY CCUS



Emitter ID	Facility	CO_2 emissions (Mt/y)	Industry sector	Trend
01	RAFFINERIE DE GRANDPUITS	0.65	Refineries	▾
02	BOREALIS GRANDPUITS	0.62	Chemicals (other)	~
03	IVRY PARIS XIII	0.59	Energy from waste	—
04	TSI	0.50	Energy from waste	▴
05	CIMENTS CALCIA USINE DE GARGENVILLE	0.19	Cement	▾
06	ROUTIÈRE DE L'EST PARISIEN (ISDND DE CLAYE SOUILLY)	0.16	Energy from waste	▾
07	CVD THIVERVAL-GRIGNON	0.13	Energy from waste	~
08	SAREN	0.13	Energy from waste	▴
09	AUROR'ENVIRONNEMENT	0.13	Energy from waste	▾
10	AZALYS	0.13	Energy from waste	▾
11	SOMOVAL	0.11	Energy from waste	—
12	GENERIS - SITE DE RUNGIS	0.10	Energy from waste	▾
13	SIAAP SITE SEINE AVAL	0.10	Energy from waste	▾
14	BOUQUEVAL ENERGIE	0.10	Energy from waste	▾
15	SARP INDUSTRIES	0.10	Energy from waste	~
16	ORVADE	0.09	Energy from waste	~
17	SAM MONTEREAU	0.09	Iron & Steel	~
18	DALKIA BIOMASSE ORLÉANS	0.08	Power	▾
19	ALPA	0.06	Iron & Steel	▴
20	GRAND PARIS SUD ENERGIE POSITIVE	0.06	Power	▴
21	SGD USINE DE SUCY EN BRIE	0.06	Glass	—
22	UIOM GIEN-CHATEAUNEUF	0.05	Energy from waste	▾
23	CVE PITHIVIERS	0.05	Energy from waste	—
24	CRISTAL UNION ETABLISSEMENT DE CORBEILLES	0.05	Food & drink	~
25	CYEL	0.05	Power	~
26	KNAUF PLÂTRES	0.05	Other	—
27	BIO SPRINGER	0.04	Food & drink	—
28	ENERTHERM NOËL PONS	0.04	Power	~
29	VELIDIS CHAUFFERIE VÉLIZY V3	0.04	Power	▾
30	VERSEO	0.04	Power	~
31	CHAUFFERIE ZUP DE SEVRAN	0.04	Power	~
32	CHAUFFERIE ZUP DE FONTENAY	0.04	Power	▾
33	PEUGEOT CITROËN POISSY SNC	0.03	Other	▾
34	SAFRAN AIRCRAFT ENGINES	0.03	Other	~
35	ETABLISSEMENT DE PITHIVIERS LE VIEIL	0.03	Food & drink	~
36	CHAUFFERIE DE PARLY 2	0.03	Power	—
37	SEMECO (ET IDEX ENERGIES)	0.03	Power	—
38	ENGIE CHAUFFERIE DE MEUDON	0.03	Power	▴
39	LESAFFRE FRERES	0.03	Food & drink	~
40	OUVRE FILS SUCRERIE ET DISTILLERIE	0.02	Food & drink	~

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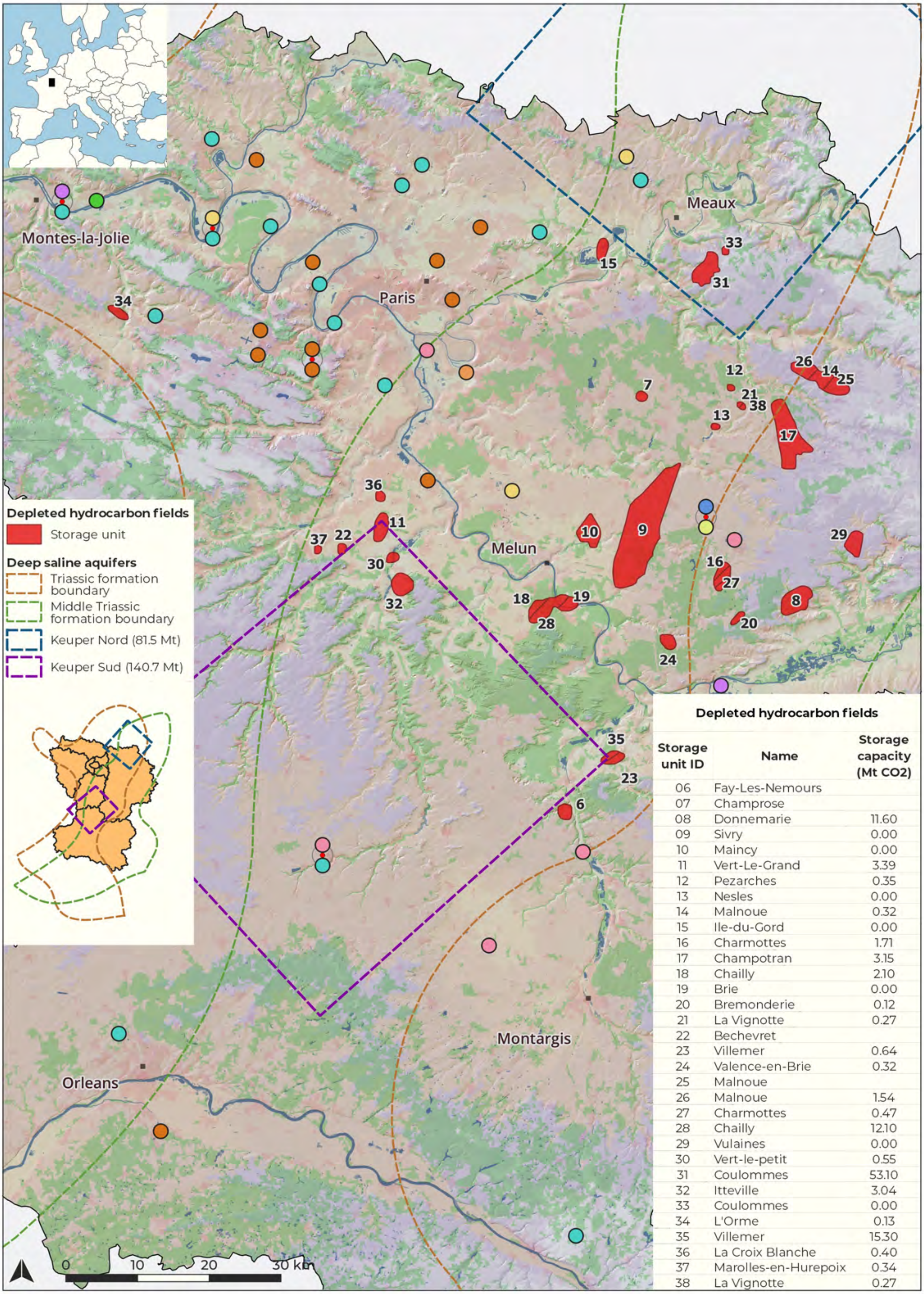
Paris basin | Storage units

STRATEGY CCUS



Depleted hydrocarbon fields

Storage unit ID	Name	Storage capacity (Mt CO2)
06	Fay-Les-Nemours	
07	Champrose	
08	Donnemarie	11.60
09	Sivry	0.00
10	Maincy	0.00
11	Vert-Le-Grand	3.39
12	Pezarches	0.35
13	Nesles	0.00
14	Malnoue	0.32
15	Ile-du-Gord	0.00
16	Charmottes	1.71
17	Champotran	3.15
18	Chailly	2.10
19	Brie	0.00
20	Bremonderie	0.12
21	La Vignotte	0.27
22	Bechevret	
23	Villemer	0.64
24	Valence-en-Brie	0.32
25	Malnoue	
26	Malnoue	1.54
27	Charmottes	0.47
28	Chailly	12.10
29	Vulaines	0.00
30	Vert-le-petit	0.55
31	Coulommes	53.10
32	Itteville	3.04
33	Coulommes	0.00
34	L'Orme	0.13
35	Villemer	15.30
36	La Croix Blanche	0.40
37	Marolles-en-Hurepoix	0.34
38	La Vignotte	0.27

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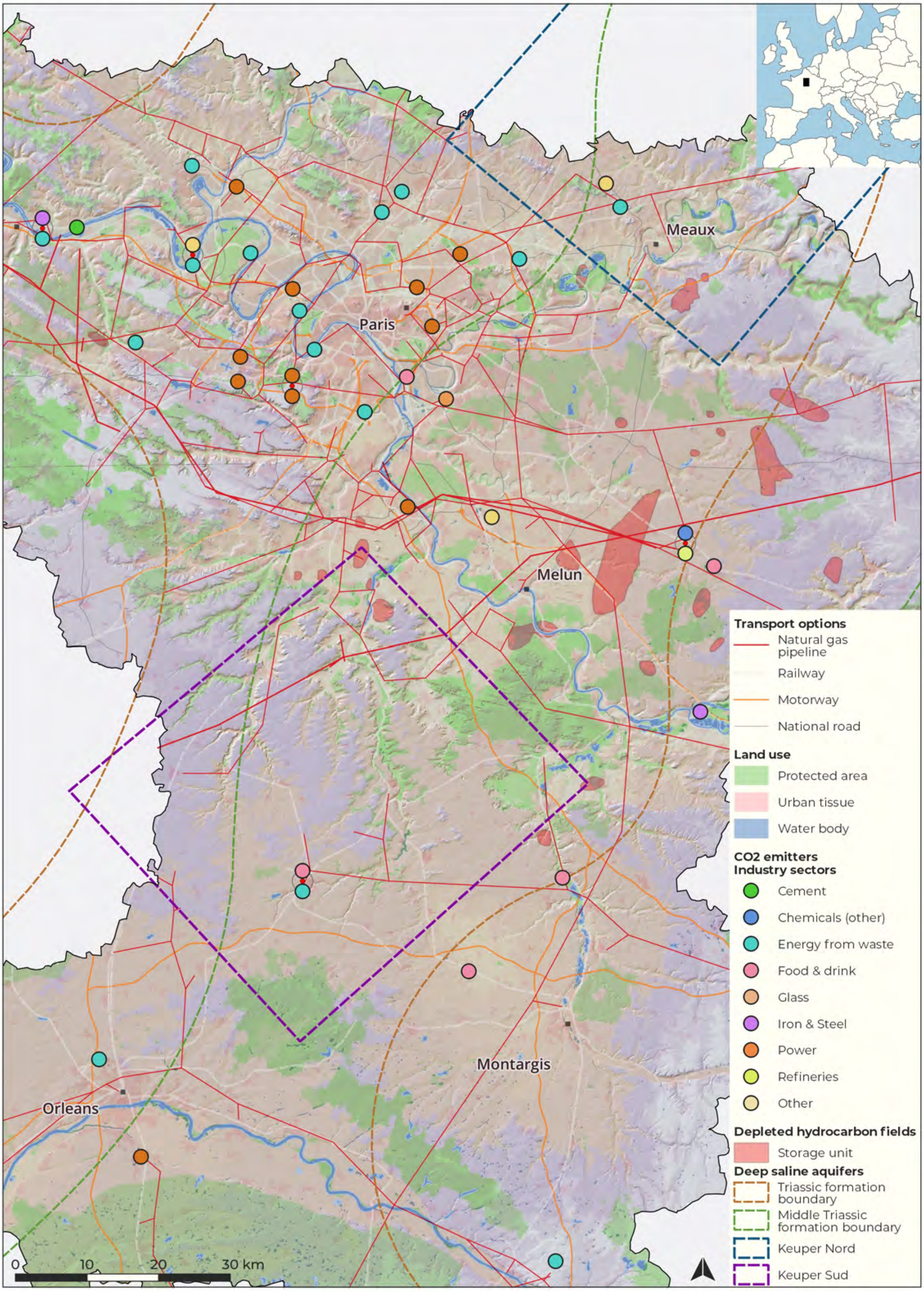
Paris basin | Transport options

STRATEGY CCUS



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Web Mercator projection (EPSG 3857)
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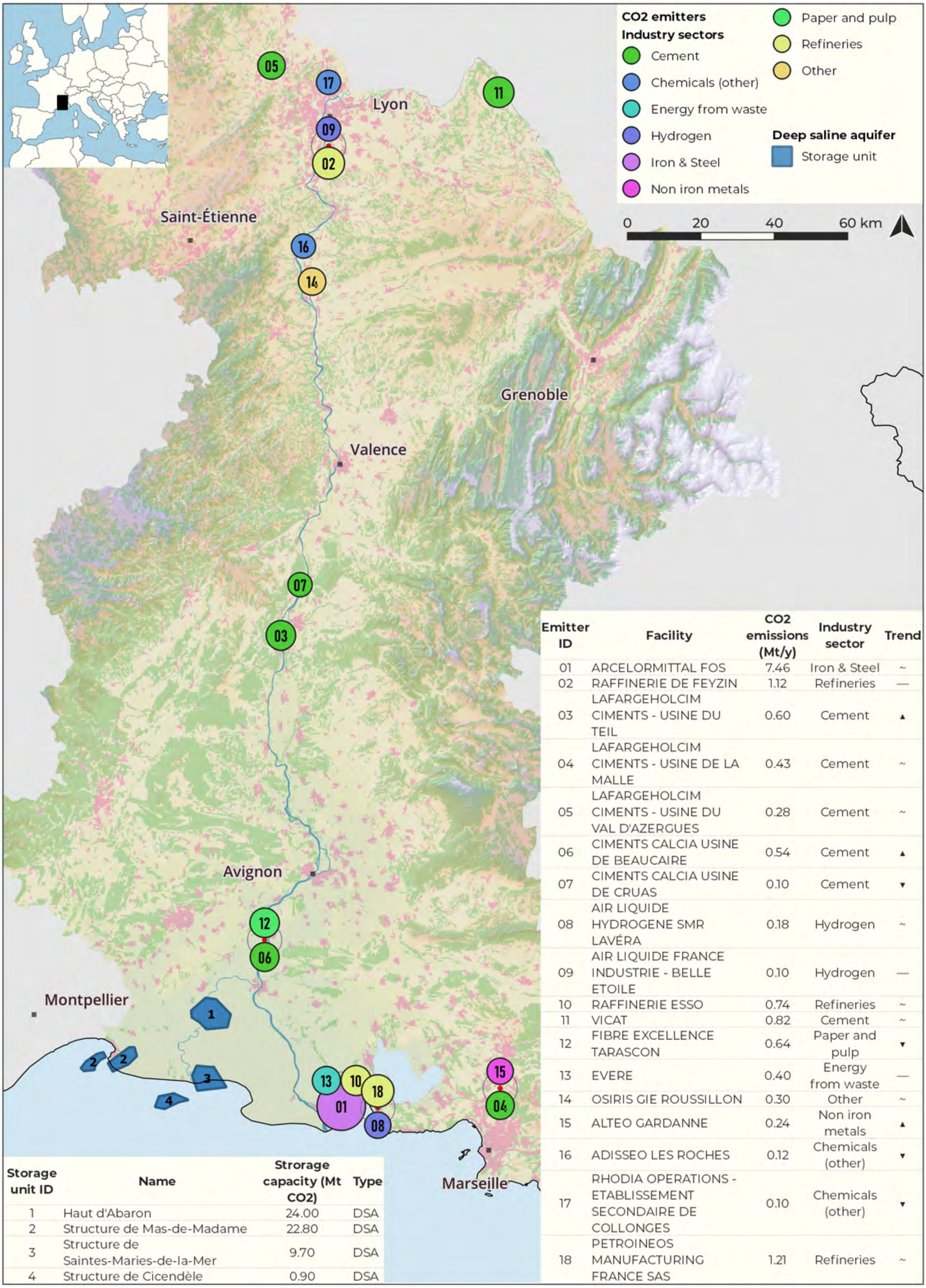
Maps of Rhone Valley

Rhone valley | Emitters and Storage units

STRATEGY CCUS



Emitter ID	Facility	CO2 emissions (Mt/y)	Industry sector	Trend
01	ARCELORMITTAL FOS	7.46	Iron & Steel	~
02	RAFFINERIE DE FEYZIN	1.12	Refineries	—
03	LAFARGEHOLCIM CIMENTS - USINE DU TEIL	0.60	Cement	▲
04	LAFARGEHOLCIM CIMENTS - USINE DE LA MALLE	0.43	Cement	~
05	LAFARGEHOLCIM CIMENTS - USINE DU VAL D'AZERGUES	0.28	Cement	~
06	CIMENTS CALCIA USINE DE BEAUCAIRE	0.54	Cement	▲
07	CIMENTS CALCIA USINE DE CRUAS	0.10	Cement	▼
08	AIR LIQUIDE HYDROGENE SMR LAVÉRA	0.18	Hydrogen	~
09	AIR LIQUIDE FRANCE INDUSTRIE - BELLE ETOILE	0.10	Hydrogen	—
10	RAFFINERIE ESSO	0.74	Refineries	~
11	VICAT	0.82	Cement	~
12	FIBRE EXCELLENCE TARASCON	0.64	Paper and pulp	▼
13	EVERE	0.40	Energy from waste	—
14	OSIRIS GIE ROUSSILLON	0.30	Other	~
15	ALTEO GARDANNE	0.24	Non iron metals	▲
16	ADISSEO LES ROCHES	0.12	Chemicals (other)	▼
17	RHODIA OPERATIONS - ETABLISSEMENT SECONDAIRE DE COLLONGES	0.10	Chemicals (other)	▼
18	PETROINEOS MANUFACTURING FRANCE SAS	1.21	Refineries	~

Storage unit ID	Name	Strorage capacity (Mt CO2)	Type
1	Haut d'Abaron	24.00	DSA
2	Structure de Mas-de-Madame	22.80	DSA
3	Structure de Saintes-Maries-de-la-Mer	9.70	DSA
4	Structure de Cicendèle	0.90	DSA

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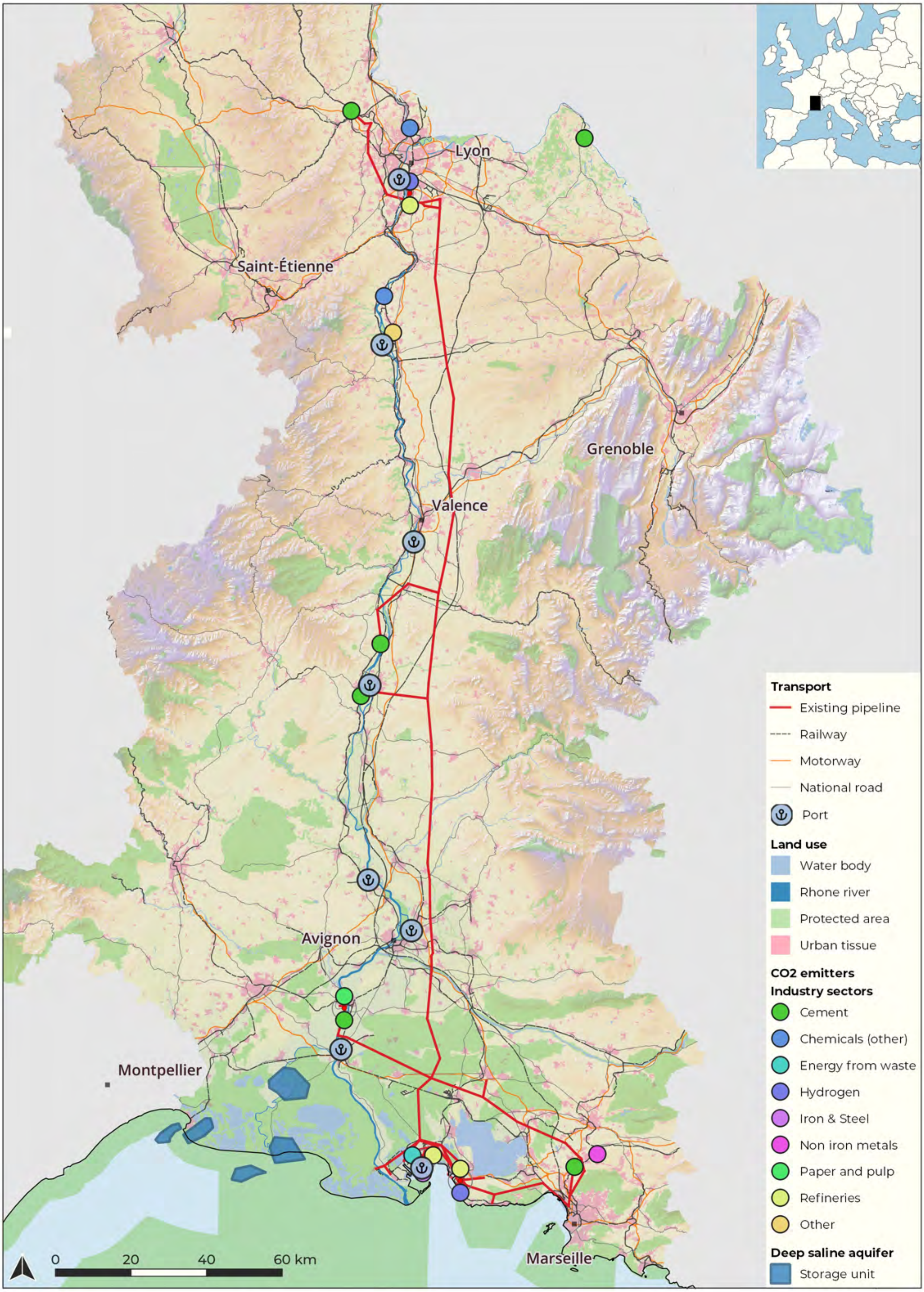
Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Rhone valley | Transport options

STRATEGY CCUS



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Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Maps of Upper Silesia

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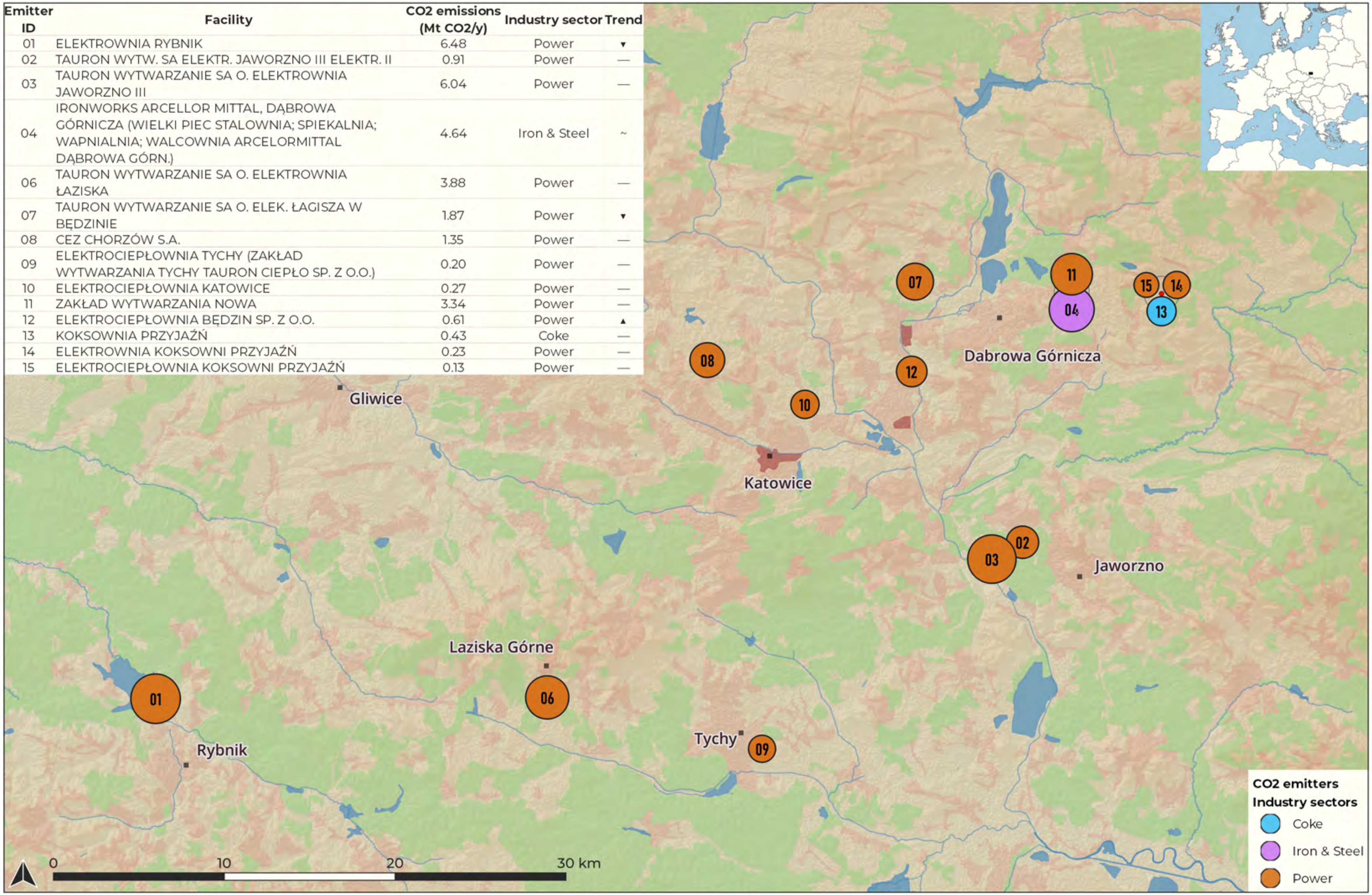
Upper Silesia | Emitters

Emitter ID	Facility	CO2 emissions (Mt CO2/y)	Industry sector	Trend
01	ELEKTROWNIA RYBNIK	6.48	Power	▼
02	TAURON WYTW. SA ELEKTR. JAWORZNO III ELEKTR. II	0.91	Power	—
03	TAURON WYTWARZANIE SA O. ELEKTROWNIA JAWORZNO III	6.04	Power	—
04	IRONWORKS ARCELLOR MITTAL, DĄBROWA GÓRNICZA (WIELKI PIEC STALOWNIA; SPIEKALNIA; WAPNIALNIA; WALCOWNIA ARCELORMITTAL DĄBROWA GÓRN.)	4.64	Iron & Steel	~
06	TAURON WYTWARZANIE SA O. ELEKTROWNIA ŁAZISKA	3.88	Power	—
07	TAURON WYTWARZANIE SA O. ELEK. ŁAGISZA W BĘDZINIE	1.87	Power	▼
08	CEZ CHORZÓW S.A.	1.35	Power	—
09	ELEKTROCIEPŁOWNIA TYCHY (ZAKŁAD WYTWARZANIA TYCHY TAURON CIEPŁO SP. Z O.O.)	0.20	Power	—
10	ELEKTROCIEPŁOWNIA KATOWICE	0.27	Power	—
11	ZAKŁAD WYTWARZANIA NOWA	3.34	Power	—
12	ELEKTROCIEPŁOWNIA BĘDZIN SP. Z O.O.	0.61	Power	▲
13	KOKSOWNIA PRZYJAŹŃ	0.43	Coke	—
14	ELEKTROWNIA KOKSOWNI PRZYJAŹŃ	0.23	Power	—
15	ELEKTROCIEPŁOWNIA KOKSOWNI PRZYJAŹŃ	0.13	Power	—



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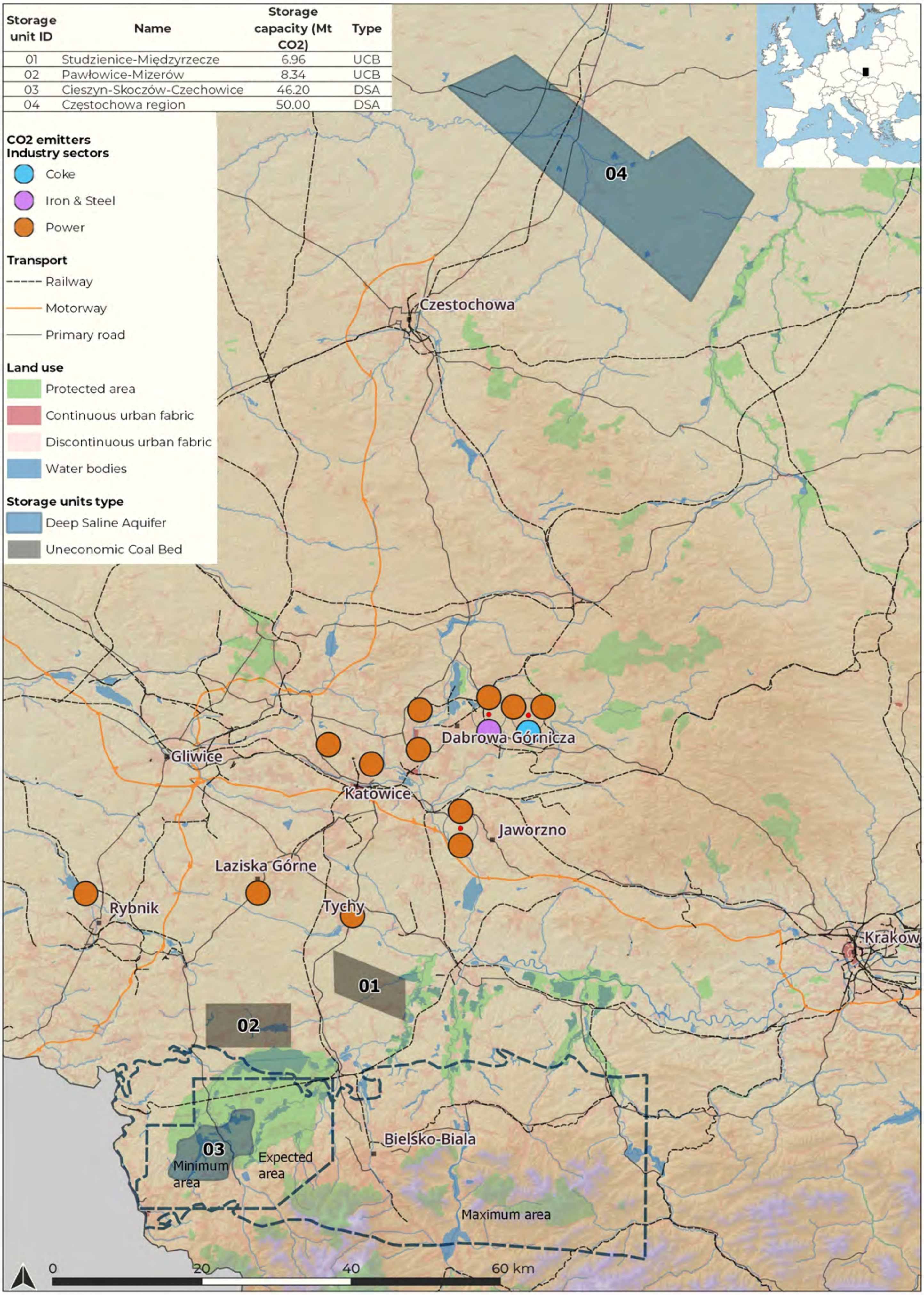
Web Mercator projection (EPSG 3857)
Points may have been displaced for visualization purposes

Upper Silesia | Transport options and Storage units

STRATEGY CCUS

Storage unit ID	Name	Storage capacity (Mt CO2)	Type
01	Studzienice-Międzyrzecze	6.96	UCB
02	Pawłowice-Mizerów	8.34	UCB
03	Cieszyn-Skoczów-Czechowice	46.20	DSA
04	Częstochowa region	50.00	DSA



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Maps of Western Macedonia

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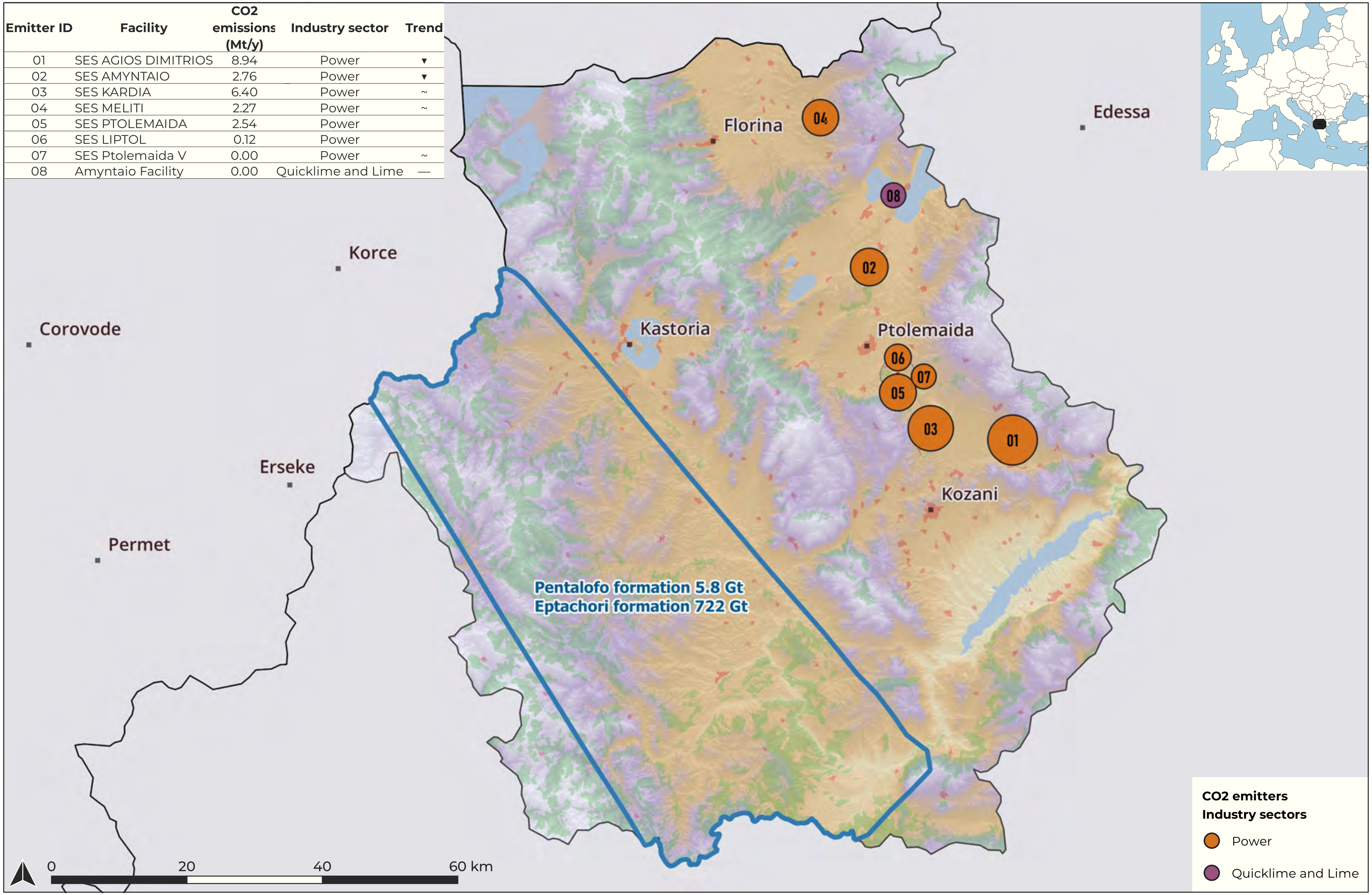
Western Macedonia | Emitters

STRATEGY CCUS

Emitter ID	Facility	CO2 emissions (Mt/y)	Industry sector	Trend
01	SES AGIOS DIMITRIOS	8.94	Power	▼
02	SES AMYNTAIO	2.76	Power	▼
03	SES KARDIA	6.40	Power	~
04	SES MELITI	2.27	Power	~
05	SES PTOLEMAIDA	2.54	Power	
06	SES LIPTOL	0.12	Power	
07	SES Ptolemaida V	0.00	Power	~
08	Amyntaio Facility	0.00	Quicklime and Lime	—



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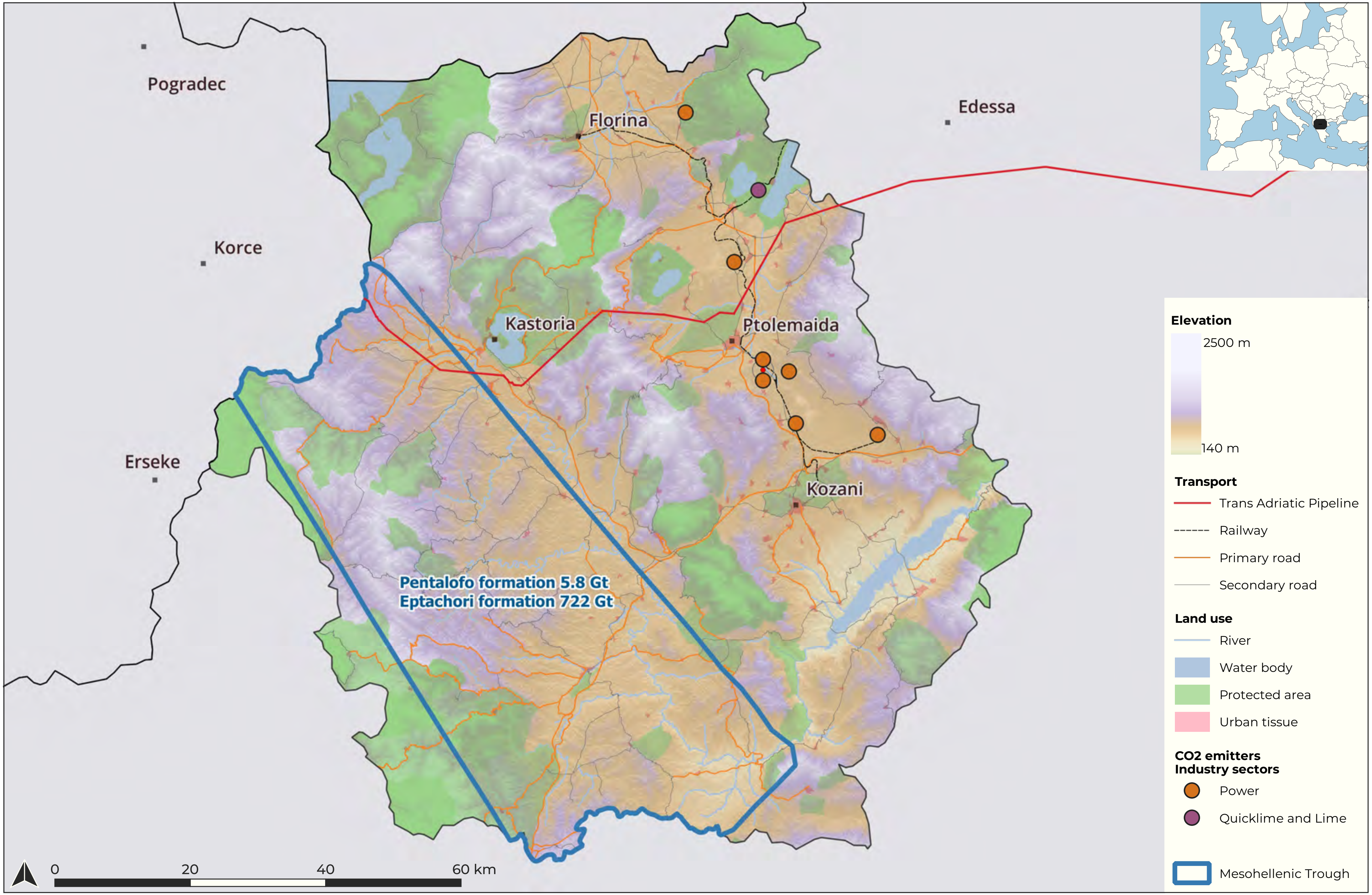
Western Macedonia | Transport options

STRATEGY CCUS



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Appendix II. Attributes of database

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CAPTURE

Basic information on industrial facilities, location and emission needed for initial emission analysis. This is likely to be available from public sources and is the initial information needed for cluster definition.		
Attribute name	Unit	Description
Emitter ID		Unique identifier for emitting facility
Company name		Company responsible for emission
Facility name		Facility name
Industry sector		Adapt from second level of NACE hierarchy
NACE code		NACE code at most detailed level identified
ETS permit ID		ETS permit code
Latitude	Decimal degrees	Latitude geographic coordinates (WGS84)
Longitude	Decimal degrees	Longitude geographic coordinates (WGS84)
City		City or town closest to the emitter
State or Province		State or province (local region) of emitter
Status		Status of emission source
CO2 from biomass combustion	t/y	Proportion of emissions attributable to biomass combustion
CO2 reported	t/yr	The reported CO2 emission from the source
Year reported		Year to which the report relates
Report basis		Reference to data source and/or method of averaging if appropriate
CO2 estimated	t/yr	Estimated CO2 emission from source if actual data not available
Year estimated		Year to which the estimate relates
Estimate basis		Estimation method or reference
Emission trend		Trend in emission year on year
Trend driver 1		What is leading to trend in emission?
Trend driver 2		What is leading to trend in emission?
Decarbonisation alternative 1		What decarbonisation alternative to CCS is practical?
Decarbonisation alternative 2		What decarbonisation alternative to CCS is practical?
Shut year		The year the emission source closed or is projected to close
Information source		Primary source(s) of information
Information source2		Alternative or additional sources, note any comments on validity
Region		Name of STRATEGY CCUS Project region
Country		Country of emission
Country Code		Two letter ISO country code
Basic technical information on processes and current flue gas properties needed for developing capture cluster options, plus any knowledge of appropriate capture technologies. This information unlikely to be available publicly, may take time to obtain through engagement with selected emitters.		
Start year		The year the emissions started, if known
CO2 concentration	%v/v	Concentration of CO2 in emission, %v/v dry basis
Composition		Is more information on composition of emission available?
Temperature	°C	Temperature of emission
Pressure	barg	Pressure of flue gas prior to emission
Flow rate, average	Nm3/s	Average volume flow rate of flue gas
Flow variation information		Is any information on emission flow variation profile available?
Process emission proportion	%	Approximate proportion of emission derived from process, rather than energy use
Number of emission points		The number of vents/emission points included in the facility's emission report
Heat availability		Is there excess heat available at the facility or close by?
Alkaline waste availability		Is there an alkaline waste stream available at the facility or close by?
Capture technology options		What is the most appropriate capture technology?
Proportionate capture rate	%	Expected proportion of CO2 that may be captured from reported emission
Capture option basis		Reference to information source for capture technology and rate
Main fuel		Main fuel used for facility energy requirement
Other fuel		Alternative or additional fuels used
Fuel use	MWh/yr	Fuel consumption
More detailed technical and production information needed for techno-economic and lifecycle analysis on selected industrial facilities. This is only needed for these further studies, but useful to collect if readily available. Some is likely to need industry engagement for actual data, or may be assumed from literature for TEA/LCA modelling purposes.		
Water content	%v/v	Water impurity content in flue gas
Hydrogen content	%v/v	Hydrogen impurity content in flue gas
Carbon monoxide content	%v/v	Carbon monoxide impurity content in flue gas
Methane content	%v/v	Methane impurity content in flue gas
Sulphur oxides content	%v/v	SOx impurity content in flue gas
Nitrogen oxides content	%v/v	NOx impurity content in flue gas
Other impurity content		Information on other impurity content in flue gas
Maximum flow	Nm3/s	Maximum volume flow rate of flue gas

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Minimum flow	Nm3/s	Minimum operational volume flow rate of flue gas
Flow variation profile description		Description of flow variation profile, if known
Main product		What is the main product of the facility?
Production	UoP	Physical production of main product of facility, units in next entry
Unit of production (UoP)		Define usual unit of production (UoP) in industry sector
Full load hours	h	Operational hours achieved in reporting year
Capacity	UoP	Nameplate capacity of plant
Unit of Capacity		Only if different from unit of production
Emission factor	t-CO2/UoP	Emission to production ratio, t-CO2/UoP
Net Generation Electricity	MWh/yr	Net Generation Electricity
Net Generation Heat	MWh/yr	Net Generation Heat
In house loads	MWh/yr	In house loads (consumption of electricity)
Gross generation	MWh/yr	Gross generation
Co-product 1		Co-product identity
Co-product 1 production	tonnes/yr	Co-product production
Co-product 2		Co-product identity
Co-product 2 production	tonnes/yr	Co-product production
Utilities, electricity	MWh/yr	Electricity usage
Utilities, water	m3/yr	Water usage
Utilities 1		Utilities name
Utilities 1 unit		Utilities usage/consumption
Utilities 1 usage		Usage/consumption unit
Utilities 2		Utilities name
Utilities 2 unit		Utilities usage/consumption
Utilities 2 usage		Usage/consumption unit
Technology		The main technology used in facility

Capture facilities - Information on potential CO2 capture facilities related to emission sources, including information on the site and existing or potential transport connections.

Attribute name	Unit	Description
Capture facility ID		Unique identifier for capture facility
Capture facility related emitters		Emitter ID, or list of emitter ID's related with the capture facility
Capture facility latitude	Decimal degrees	Latitude geographic coordinate (WGS84) if a location is defined
Capture facility longitude	Decimal degrees	Longitude geographic coordinate (WGS84) if a location is defined
Capture facility, source of information		What is the basis of this capture facility location?
Estimated capture volume	t/yr	Estimate of potential CO2 capture volume at facility
Space available at facility		Description of space available, beyond that needed for basic capture unit
Expected CO2 condition at facility - Pressure	barg	
Expected CO2 condition at facility - Temperature	°C	
Road access at facility		Confirm HGV access
Existing bulk liquid loading to road at site		
Existing CO2 loading station nearby		
Existing CO2 loading station nearby information		
Permitted road tanker load	t	
Road transport constraints		
Rail access at facility		Potential rail access?
Status of rail branch		
Distance to branch from capture facility	km	
Existing rail terminal at site		
Existing bulk liquid loading to rail at site		
Waterway access at site		Potential waterway access?
Port(s) ID		Unique ID's of the port(s) capable of providing waterway access to the facility
Distance to port from capture facility	km	
Potential for pipeline access at capture facility		Potential pipeline access?
Pipeline (s) ID		Unique ID's of the pipelines capable of being accessed by the facility
Existing pipeline corridors close to site		Potential pipeline corridor access?
Pipeline corridors ID		Unique ID's of the pipeline corridors close to the facility
Distance to pipeline/corridor from capture facility	km	

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Remarks		Any other relevant comments.
Potential collection hubs - Information on potential hubs for collection of CO2 within the cluster area, including processing requirements, and on the options for onward transport to storage area.		
Attribute name	Unit	Description
Hub ID		Unique identifier for potential hub
Hub latitude	decimal degrees	Latitude geographic coordinate (WGS84) if a location is defined
Hub longitude	decimal degrees	Longitude geographic coordinate (WGS84) if a location is defined
Potential collection hub, source of information		What is the basis of this hub location?
Processing requirement at hub location		What processing or conditioning of CO2 will be required at the collection hub?
Resource availability at hub location		Are there resources at the hub that can be used for processing?
Expected CO2 condition at collection hub - Pressure	barg	
Expected CO2 condition at collection hub - Temperature	°C	
Road transport available		Road transport connection available at the hub?
Rail transport available		Rail transport connection available at the hub?
Waterway/sea transport available		Waterway/sea transport connection available at the hub?
Port transport ID		Port ID's of the port(s) capable of providing transport connection
Existing pipeline transport available		Existing pipeline transport connection available at the hub?
Existing pipeline ID		Pipeline ID's of the pipeline(s) capable of providing transport connection
Pipeline corridor available		Pipeline corridor connection available at the hub?
Pipeline corridor ID		Pipeline corridor ID's of the pipeline corridor(s) capable of providing transport connection
Trunk transport option shipping		Is it likely onward trunk transport mode by shipping?
Trunk ports ID		Port ID's of the port(s) likely to provide trunk transport shipping access
Trunk transport option existing pipeline		Is it likely onward trunk transport mode by existing pipeline?
Trunk pipeline ID		Pipeline ID's of the pipeline(s)likely to provide trunk transport pipeline access
Trunk transport option new pipeline		Is it likely onward trunk transport mode by new pipeline?
Storage location options		ID's of the storage location options
Remarks		Any other comments about a specific attribute or potential capture hub in general.
Cluster area - General information on the cluster area, and on existing or potential transport infrastructure in the wider region, for onward transport to storage area.		
Attribute name	Unit	Description
Cluster ID		Unique identifier for cluster
Cluster Name		Cluster name
Emitters(s) ID		Which emitters are included in capture cluster, may be related to different development phases
Collection hub location options		Hub options, may be several, or may be related to different development phases
Estimated cluster capture volumes	t/yr	Total capture from cluster, may be related to different development phases
Development phase		Development phase identifier
Storage(s) ID		Which storage sites may be used?
Trunk transport option Shipping		Is bulk transport to storage by ship an option?
Trunk transport option Existing pipeline		Is there an existing pipeline that might be used for trunk transport?
Trunk transport option New pipeline		Is a new pipeline necessary for trunk transport?
Available rail tank-car capacity	m3	Capacity of tank-cars for lease
Rail tank-car length	m	Length of tank-cars for lease
Permitted train length	m	General rail system, or local/regional restriction
Permitted road tanker load	tonnes	General regional/national road transport load restriction
Existing pipeline availability		Are there existing pipelines that may be available for collection network?
Existing pipelines ID's		Pipeline(s) ID's of existing pipelines that may be available for collection network
Pipeline corridors availability		Are there existing pipeline corridors that may be available for collection network?
Pipeline corridors ID		Pipeline corridor(s) ID's of existing pipeline corridors that may be available for collection network
Remarks		Any other comments about a specific attribute or cluster area in general

STORAGE

Storage Unit - Geographic identification of location of STORAGE UNIT, DAUGHTER UNIT or PROSPECT		
Attribute name	Unit	Description
STORAGE_UNIT_ID		Unique identifier for this storage unit
STORAGE TYPE		Deep Saline aquifer, Depleted Hydrocarbon Field, Uneconomic Coal Bed
STORAGE_UNIT		Name of storage unit
FORMATION		Name of storage formation
DAUGHTER _UNIT		Name of Daughter_Unit

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PROSPECT		Name of Prospect
FIELD_HC_CONTENT		Hydrocarbon type: oil, gas, condensate
FIELD_STATUS		Current statut of DHF: Producing, Suspended, Abandoned
FIELD_AVAILABILITY		Year when CO2 injection can commence
DATE_ENTERED		Date of data entry
REGION		Name of promising region
COUNTRY		Name of country
COUNTRY_CODE		ISO country code
Geology - Geological parameters of reservoir		
Attribute name	Unit	Description
STORAGE_UNIT_ID		Unique identifier for this storage unit
LATITUDE	Degrees	X WGS84 decimal degrees for central point or representative borehole
LONGITUDE	Degrees	Y WGS84 decimal degrees for central point or representative borehole
ELEVATION	m	Mean surface elevation for onshore reservoirs or water depth for offshore reservoirs.
ELEVATION_DATUM		Datum used for elevation
GEOGRAPHIC_AREA		Surface location
ON_OFF_SHORE		Onshore or offshore
Storage unit parameters - Detailed information about reservoir unit		
Attribute name	Unit	Description
UNIT_AREA_EXPECTED	km2	Representative area, expected
UNIT_AREA_MAXIMUM	km2	Representative area, maximum
UNIT_AREA_MINIMUM	km2	Representative area, minimum
UNIT_AREA_NET_TO_GROSS	%	Expected net to gross for storage area
UNIT_DEPTH_TOP	m	Average depth to top of unit or at representative borehole
UNIT_THICKNESS	m	Representative thickness, expected
UNIT_THICKNESS_MAXIMUM	m	Representative thickness, maximum
UNIT_THICKNESS_MINIMUM	m	Representative thickness, minimum
UNIT_THICK_NET_TO_GROSS	%	Expected net to gross for thickness
PERFORATION_FRACTION	%	Well perforation as a fraction of thickness
POROSITY_TYPE		Indicate if primary or secondary porosity type.
HETEROGENEITY_ESTIMATE		Estimate of heterogeneity on permeability according to the VPD, Dykstra-Parsons coefficient of permeability variation
UNIT_POROSITY_EXPECTED	%	Representative porosity, expected
UNIT_POROSITY_MAXIMUM	%	Representative porosity, maximum
UNIT_POROSITY_MINIMUM	%	Representative porosity, minimum
UNIT_PERMEABILITY	mD	Representative permeability, expected
UNIT_PERM_MAXIMUM	mD	Representative permeability, maximum
UNIT_PERM_MINIMUM	mD	Representative permeability, minimum
UNIT_COMPRESSIBILITY	1/MPa	Representative bulk compressibility
UNIT_DENSITY	kg/m^3	Bank density of coal, RHOCOAL
UNIT_DENSITY_MAXIMUM	kg/m^3	Bank density maximum
UNIT_DENSITY_MINIMUM	kg/m^3	Bank density minimum
ASH_CONTENT	%	Fraction of coal that is ash, fa
ASH_CONTENT_MAXIMUM	%	Maximum fraction of coal that is ash
ASH_CONTENT_MINIMUM	%	Minimum fraction of coal that is ash
MOISTURE_CONTENT	%	Fraction of coal that is moisture, fm
MOISTURE_CONTENT_MAX	%	Maximum moisture fraction
MOISTURE_CONTENT_MIN	%	Minimum moisture fraction
Storage fluid parameters - Information about expected CO2 storage conditions		
Attribute name	Unit	Description
UNIT_TEMPERATURE	°C	Representative temperature
UNIT_PRESSURE	MPa	Representative pressure
CO2_DENSITY	kg/m^3	Representative CO2 density, expected
CO2_DENSITY_MAXIMUM	kg/m^3	CO2 density, maximum
CO2_DENSITY_MINIMUM	kg/m^3	CO2 density, minimum
PORE_WATER_SALINITY	ppm	Pore water salinity
WATER_SATURATION	%	Expected water fraction in field
WATER_SAT_MAX	%	Maximum water fraction in field
WATER_SAT_MIN	%	Minimum water fraction in field
RECOVERY_FACTOR	%	Fraction of hydrocarbon recovered
RECOVERY_FACTOR_MAX	%	Maximum fraction of recovered HC
RECOVERY_FACTOR_MIN	%	Minimum fraction of recovered HC
UNIT_TEMPERATURE_MAX	°C	Isotherm temperature, maximum
UNIT_TEMPERATURE_MIN	°C	Isotherm temperature, minimum
UNIT_PRESSURE	MPa	Representative pressure, P

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UNIT_PRESSURE_MAX	MPa	Maximum pressure, P
UNIT_PRESSURE_MIN	MPa	Minimum pressure, P
LANGMUIR_PRESSURE	MPa	Critical desoprtion pressure, PL
LANGMUIR_PRESSURE_MAX	MPa	Desoprtion pressure, maximum
LANGMUIR_PRESSURE_MIN	MPa	Desoprtion pressure, minimum
LANGMUIR_VOLUME	scf/tonne	Aadsorbed gas content, VL
LANGMUIR_VOLUME_MAX	scf/tonne	Adsorbed gas content, maximum
LANGMUIR_VOLUME_MIN	scf/tonne	Adsorbed gas content, minimum
Seal - Geological parameters of seal		
Attribute name	Unit	Description
SEAL		Name of the primary seal, the main seal providing containment to the storage site
SEAL_LITHOLOGY		Representative lithology
SEAL_THICKNESS	m	Number of secondary seals, low permeability units in the stratigraphy above the primary seal that provide secondary containment if the primary seal fails
SECONDARY_SEALS	m	Number of secondary seals
SEAL_FAULT		Qualitative evaluation of seal quality: high/low for fractures and faults. See table in worksheet BSA for reference.
Storage efficiency - Information required for selecting storage efficiency to be applied for storage capacity calculations		
Attribute name	Unit	Description
UNIT_BOUNDARY_CONDITION		Boundary condition of the prospect: Open, closed, semi-closed, unknown
SEF_CLASS		Storage Efficiency Factor class: Global, Regional
SEF_VALUE	%	Value of Storage Efficiency Factor applied in previous storage capacity estimates
Previous estimates - Data on methods and values of existing storage capacity and injectivtiy estimates from previous studies and projects		
Attribute name	Unit	Description
STORAGE_CAPACITY	Mt	Previous expected storage capacity of unit
STORAGE_CAPACITY_RANGE	Mt	Previous storage capacity range
INJECTIVITY_EXPECTED	mDm	Previous estimate of injectivity
INJECTIVITY_RANGE	MDm	Max-Min range for injectivity
SOURCE_ESTIMATES		Source from which estimates are taken
METHODOLOGIES		Methodologies applied in capacity and injectivity estimates
Injectivity - Information required for injection rates estimates. Tier 3 data, required to be fill only if a PROSPECT has been identified in worksheet STORAGE UNIT		
Attribute name	Unit	Description
HYDROSTATIC_PRESSURE	MPa	Hydrostatic pressure at injection depth
AMBIENT_PRESSURE	MPa	Reservoir pressure at injection start
LITHOSTATIC_PRESSURE	MPa	Lithostatic pressure at seal/reservoir
FRACTURE_PRESSURE	MPa	Fracture pressure of seal
PRESSURE_HEADSPACE	MPa	Fracture pressure - Ambient pressure
INJECTION_RATE	MT/Yr/Well	Expected injection rate for a vertical well
INJECTION_DURATION	Years/Well	Expected duration of injection for a well

CO2-EOR

Attribute name	Unit	Description
STORAGE_UNIT_ID		Unique identifier for this storage unit
STORAGE TYPE		Depleted Hydrocarbon Field
U1	stb	Recoverable Oil Volume
U2	bbl/stb	Reservoir Volume Factor
U3	m3	Water Injection-Production Balance
U4	Mt	CO2 Required to Produce Oil Volume
U5		Miscible Flood and WAG Suitability
U6		Alternative Injection Strategy (Gravity?)
U7		IEA Model Class for CCUS (1,2,3)
U8		Strength of Aquifer Support (High/Low)
REGION		Name of promising region
COUNTRY		Name of country
COUNTRY_CODE		ISO country code
REMARKS		Any other relevant information

CO_2 Utilisation

Attribute name	Unit	Description
USE_UNIT_ID		Unique identifier for this utilisation unit
UTILISATION_TYPE		Type of utilisation (fuels, chemicals, building materials, enhanced recovery…)
PRODUCT		product or service resulting from CO2 utilisation
CONVERSION_USE		
STATUS		Current status of facility or planning

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START_YEAR		Year of start of operations (effective or planned)
COMPANY_NAME		Company responsible for utilisation
FACILITY_NAME		Facility name
LATITUDE	Decimal degrees	Latitude geographic coordinates (WGS84)
LONGITUDE	Decimal degrees	Longitude geographic coordinates (WGS84)
CITY		City or town closest to the facility utilising CO2.
STATE PROVINCE		State or province (local region) of facility utilising CO2
CO2 USED	t/y	Total amount of CO2 estimated to be used per year
SOURCE CO2		Source of CO2 being or to be used
CO2 EMITTED	t/y	Total amount of CO2 estimated to be emitted by the facility per year
IMPACT	t/y	Difference between CO2 used and emmitted
UNITS PRODUCED	units/y	Units of PRODUCT per year
MAIN FUEL		Main fuel used at facility
FUEL USE	MWh/yr	Fuel consumption
DISPLACEMENT		Product or service the CO2-based product or service displaces
ACCOUNTING		How is the accounting of CO2 used and emmitted monitored and verified.
YEAR REPORT		Year to which the reporting relates
INFO SOURCE		Primary source(s) of information
REGION		Name of promising region
COUNTRY		Name of country
COUNTRY CODE		ISO country code
REMARKS		Any other relevant information

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