Cost-effectiveness of storage sites and comparison of promising regions

Release Status: Public

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Date: June 2022

Filename and version: D4.5_Cost-effective_DATE.doc

Project ID NUMBER 837754

STRATEGY CCUS (H2020-LC-SC3-2018-2019-2020/H2020-LC-SC3-2018-NZE-CC)

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

Document History

Location

This document is stored in the following location:

Filename	D4.5_Cost-effective storage site 17062022
Location	Project website: https://www.strategyccus.eu/project-outputs/economics-outputs

Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename/Location stored:	Brief Summary of Changes
Draft#1	07/04/2022	Sharepoint WP4/task4.5	Version to be revised by local teams
Draft#2	02/05/2022	Sharepoint WP4/task4.5	Compiled version to be filled and verified by local teams
Draft#3	01/06/2022	Sharepoint WP4/task4.5	New tables and pre-final version
Final draft	17/06/2022	Sharepoint WP4/task4.5	Final version

Authorisation

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Distribution

This document has been distributed to:

Name	Title	Version Issued	Date of Issue
		Public	00/00/0000

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Chen, L. 2022. D4.5 Cost-effectiveness of storage sites and comparison of promising regions, 31 pages. EU H2020 STRATEGY CCUS. Project 837754

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Executive summary

There are two main objectives of this deliverable D4.5. The first one is to provide assessment of storage bankability, based on the outcome from WP2 (Mapping technical aspects), and to estimate the cost repartition along storage life cycle: from exploration, to operation, till monitoring. The second one is to focus on the components of business models, i.g. revenue model (policy support mechanism), ownership structures, to discuss the suitable business model for the studied regions.

The results show that, all storage sites in studied regions have not reached bankability status. The deployment time of increasing storage site maturity to bankability status may take between 5 to 10 years, depending on the current maturity and exploration loops. This finding suggests the necessity to carry out relevant work from today. The costs of storage per CO_2 tonne stored (capex + opex) is a function of the quantity of CO_2 been stored with low values for onshore option, as in Upper Silesia. These costs vary from 14 €/tonne of CO_2 stored (Lusitania Basin onshore) to 60 €/tonne of CO_2 stored (Galati region).

Costs to reach a bankability status in these eight regions are the pre-FID (Final Investment Decision) costs. Pre-FID costs estimated in STRATEGY CCUS regions represent between 1% (Galati Region) to 6% (Rhone Valley region) of total storage costs (Capex[1]+Opex[2]), which is less than the expected costs of 10% to 75% estimated by ZEP (2011).

Governments and private company alliances seem to be the key financial support providers.

Concerning the revenue models, today, most existing CCS projects receive policy supports. There are various supports (European levels or national levels), and in various forms (subsidy, specific contracts, etc). National funding possibilities exist as well, even they are not specific for CCUS. In the longer term, these supports are believed to evolve together with EU ETS system to ensure business profitability.

CCUS is a long value chain, involves many sectors (power, cement, steel, refinery, oil & gas, shipping, pipeline, etc) and hence various ownership models have been discussed (from vertically-integrated, to operator business models). It is recommended to segment CCS chain into 2 parts (CO2 capture, and CO2 transport/storage) or 3 parts (CO2 capture, CO2 transport, and CO2 storage), in order to bring down market entrance barrier and allow more companies to participate in the market. Then for each part, Joint-Venture model is recommended in order to further share risks and accelerate development.

[1] Capital Investment costs
[2] Operational costs

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Cost-effectiveness of storage sites and comparison of promising regions

1 Introduction

The objective of this report is to provide assessment on the storage bankability, and discuss the potential business models that can be applied in the studied regions.

Storage sites identification has been investigated in WP2 (Mapping Technical Aspects), hence the first part of this report is a continuity of analysing outcome from WP2. As already observed in WP2, storage sites in the studied region have relatively low maturity and cannot be considered bankable. Therefore, the first part of current report is dedicated to understanding the impact of increasing storage maturity to the CCS project development time and additional cost. Global CCS project costs and costs of each element of the chain (capture, transport and storage) have been investigated in WP5 (Elaborating CCUS scenarios), although these costs consider storage sites as mature. The additional cost related to CO2 storage site exploration and characterisation to make it bankable will be compared to mature CCS project cost.

The second focus of this report is on the business model. Up to now, there are few massive CCS projects worldwide and the business model is case by case. Hence, the particular focus is to look for the common points among these projects, the role of policy support & funding mechanisms. Finally, CCS represents a long value chain and involve various sectors: power producers, industries (cement, steel, refinery, etc), shipping & pipeline operators and oil & gas majors. What would be the ownership modes, how CCS value chain segmented are discussed as well in order to propose a suitable recommendation for studied regions.

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2 Storage maturity, its impact on bankability and effective cost

2.1 Storage maturity in studied regions

Storage maturity assessments were carried out in D2.3[3] (Maturity level and confidence), and key results are presented in Figure 1. Using the qualitative assessment to describe storage capacity as recommended in D2.1[4] (Best Practice), within DSA and DHF assets, regions reported 60 DSA prospects with 45 described as Tiers2 and 15 as Tiers1 and 50 DHF prospects, which are by definition Tiers2 resource (Figure 1). Two regions estimated storage capacity for DSA resources through reservoir simulation studies: Paris Basin (FR) and Upper Silesia (PL). Also, For EOR calculation, North of Croatia (HR) supplied data for 15 years of CO_2 injection based on simulation studies.

Three most important resources within regions are those described as T1 and represent 7.45 Gt of available capacity for DSA. The volumetric calculation was used to estimate the majority of T2 (and T1) resources of STRATEGY CCUS regions. These capacities were previously estimated in past European o National project as Geocapacities; CO2STOP; COMET; and other national research projects such as ALGECO2; France Nord; VASCO; etc. The calculation made in these projects adopts assumptions in order to take into account reservoir heterogeneity, CO_2 and rock compressibility, changes in temperature and pressure, etc.

The T2 resources calculated through reservoir modelling supply additional information about the injection rate and number of wells to develop a given storage potential. Usually, simulation studies of CO_2 injection limit the injection rate to the reservoir pressure below the leak-off pressure. The injection rate is then planned assuming the need of multiple wells and/or the production (extraction) of formation reservoir brine (water).

Therefore, estimated capacity reported here is more conservative than in previous projects in some regions where data is insufficient, as in Rhone Valley (FR) and West Macedonia (GR). In these regions a SEF (storage efficiency factor) of 2% was applied. In other cases as in Lusitania Basin, new seismic and wellbore data allowed more optimist region's assumptions and new calculation were performed using a SEF of > 2%

[3] https://www.strategyccus.eu/sites/default/files/D2.3_StorageResourcesManagement_DRAFT.pdf
[4] https://strategyccus.eu/project-outputs/methods-outputs

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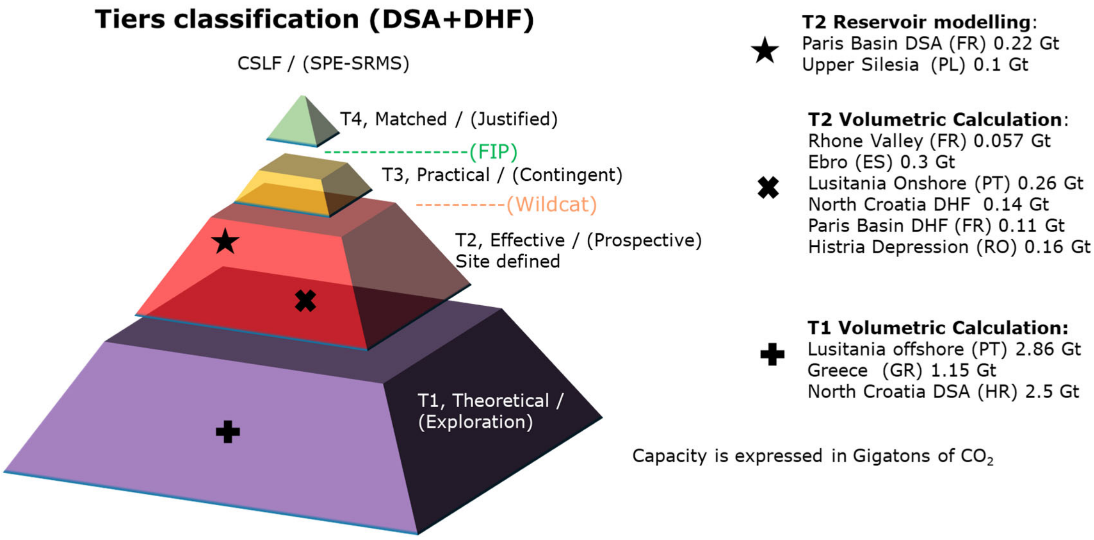

Figure 1: Tiers classification of storage sites in studied regions (D2.3[5])

It is worth recalling that tiers are described as follows:

- Tier 1 - Regional assessment, the lowest tier, equivalent to Exploration (Theoretical), with
- generic global or regional SEFs.
- Tier 2 - Discovery assessment, equivalent to Prospective (Effective), with tailored SEFs.
- Tier 3 - Prospect assessment, equivalent to Contingent and pending/on hold (Practical), detailed data, prospective candidates.
- Tier 4 - Site assessment; equivalent to Justified/Approved/On Injection (Matched), site project.

One of the key challenge is the uncertainty of storage resource capacity at long-term scale.

The interpretation of storage maturity impact on project bankability is assessed in next section.

2.2 Bankability

A storage site is bankable when sufficient confidence exists in technical and cost elements to support final decisions for deploying commercial-scale investment (IEAGHG, 2011). Workflows to identify the main project tasks required to achieve bankable status for commercial scale storage projects in deep saline aquifers (DSA), depleted oil and gas reservoir (DHR) and CO_2 enhanced oil recovery (CO_2-EOR) schemes have been investigated in (IEAGHG, 2011). Databases of storage projects from IEA GHG,

[5] D2.3 Maturity level and confidence of storage capacities estimates in the promising regions

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Global CCS Institute, MIT, Bellona, Scottish Centre CCS and CO2CRC, and DOE-NETL have been served as input.

An example workflow for DSA is given below.

Type of study	Phase	Major costs items
National based *Non exclusive surveys*	Phase 0 Screening	First desktop studies
Project based *Exclusive surveys*	Phase 1 Desk Based assessment	Desktop studies, where possible seismic reprocessing and existing wells logs analysis (inluding communication on project)
	Licensing Exploration Permit	Admistrative engineering and follow-up
	Phase 2 Site confirmation & characterization	Studies and engineering for this phase (including monitoring actions, equipments and monitoring (soil, gravimetric, Insar)) Seismic acquisitions 2D Seismic acquisitions 3D (on CO_2 future plume only) Civil Engineering Drilling CO_2 well with rotary rig (including 20% contingency including Mob/demob)
	Licensing Injection test	Injection test permitting
	Phase 2 Injection Test	Studies and monitoring Injection test duration CO_2 injection cost
Bankable		

Figure 2: Steps to reach bankable storage status for Onshore Deep Saline Formation (IEAGHG, 2011)

When comparing this assessment method to the method used in WP2 (D2.1[6]), it means that CO_2 storage resources should be classified as at least Tier3 (Contingent) and ideally as Tier4 (Matched) to become bankable. However, results in the precedent section show that all storage resources in the current project are classified below Tiers3, which means that they are not yet bankable.

In a CCS project, CO_2 storage field capacity should be enough to store 30-40 years of emissions with an injection rate adapted to the CO_2 flow rate from industrial/power installations. It is necessary to carry out further work to increase storage capacity maturity to bankable status.

[6] Methodologies for cluster development and best practices for data collection in the promising regions

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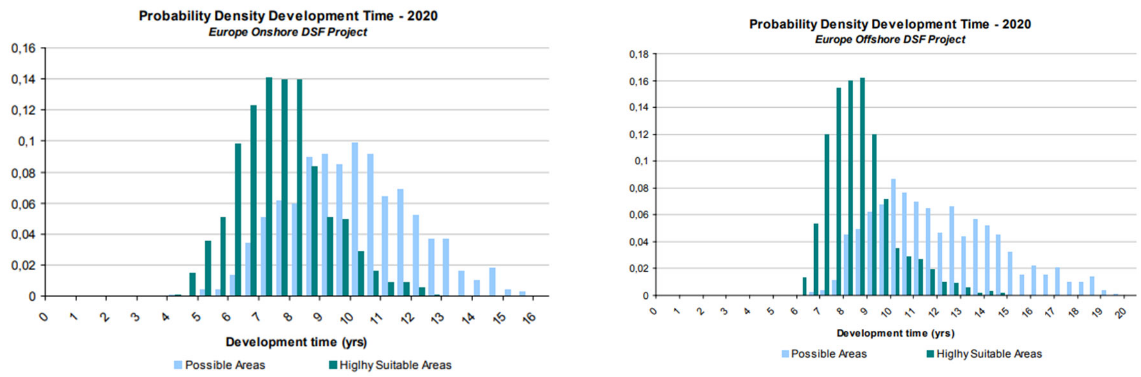
2.3 Impact on CCS project deployment time

Like all activities related to geology, storage operations are not straight forward. Taking Northern Light project as example, the exploitation permit had been awarded in January 2019, while end of 2021 three years later, green light of final investment decision was made. It is expected to be operational in 2024. It is crucial to understand how long it may take to increase storage maturity, as the delay of project due to storage maturity may lead to the failure of regional decarbonisation target achievement.

Based on the workflow in Figure 2, modelling have been carried out to estimate the necessary time and cost to reach bankable status. Storage site development study is iterative. In order to take into account the impact of iterative loops in the time estimation, two scenarios have been developed: possible areas representing higher number of loops, and highly suitable arears representing lower number of loops.

Details on the modelling assumptions can be found in (IEAGHG, 2011), key results are extracted and presented in Figure 3.



(a) Deep Saline Formation Onshore (b) Deep Saline Formation Offshore

Figure 3: – Development Time Distribution For Highly Suitable and Possible areas for EU storage projects (IEAGHG, 2011)

As showed in Figure 3, for onshore project, it may take from 5 to 15 years, with peak values around 8, to develop storage projects in highly suitable areas and 10 years in possible arears. For offshore storage projects, the timing needed to develop projects are from 5 to 19 years, with peak values around 9 years in highly suitable areas and 11 years in possible areas. Half of the development time are determined by licensing and environmental issues.

Based on these assessments, it is clear that if we plan to start CCS project in 10 years, we must begin to increase CO_2 storage maturity today, with no delay.

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2.4 Impact on CO2 storage cost and CCS cost

Life cycle cost of CO_2 storage per phase have been investigated and reported in (ZEP, 2011). Pre-FID phase includes an initial screening of multiple sites, the characterisation of selected site(s) and the permitting process. It is compatible with the cost to increase storage maturity into bankable.

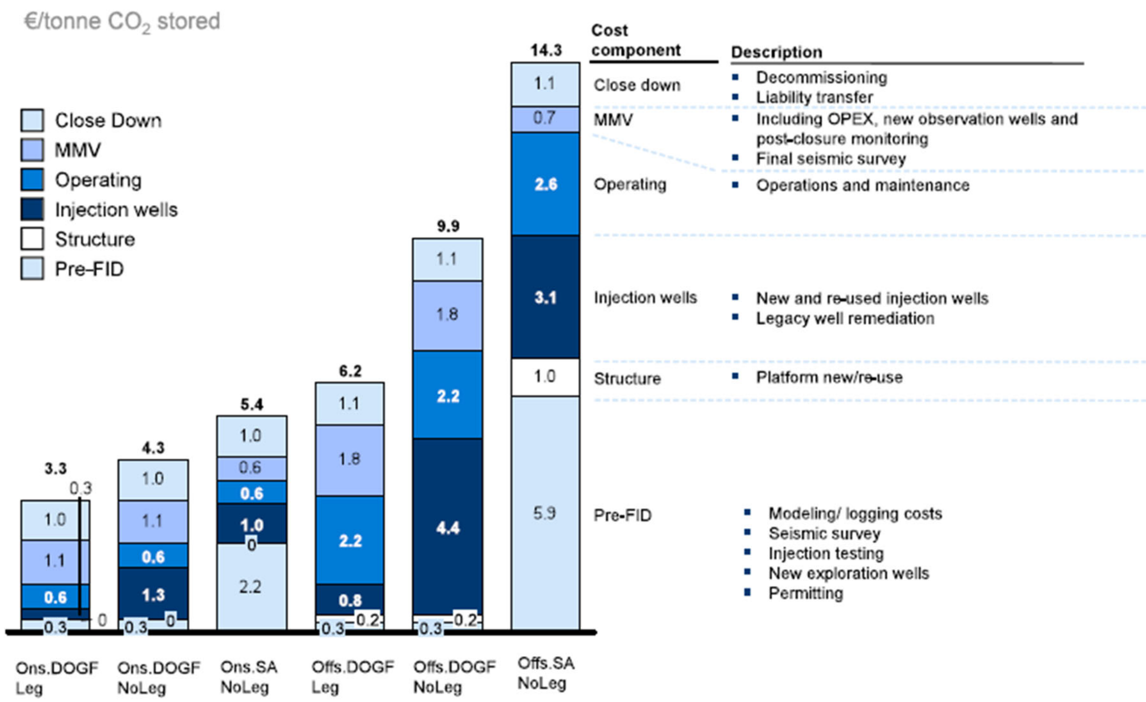

Figure 4: CCS cost breakdown per phase for onshore (ons.), offshore (offs.), Depleted Oil and Gas Field (DOGF), Saline Aquifer (SA) and possibility of re-using existing infrastructure (leg.) (ZEP, 2011)

Cost of increasing storage maturity (pre-FID phase in Figure 4) represents between 10% and 75% of the cost of rest of storage life cycle, depending on storage site specificity (onshore or offshore, SA or DOGF). It is between 0.3 €/ton CO_2 to 6 €/ton CO_2, in front of a total life CO_2 storage cost between 3.3 and 14.3 €/t CO_2.

Key differences are explained by the fact that offshore is more expensive than onshore and Saline Aquifer (SA) is more expensive than DOGF (Depleted Oil & Gas Field).

2.5 Focus on the studied regions

Storage resources of STRATEGY CCUS regions represent different geological settings onshore and offshore. The level of confidence for the CO_2 storage capacity estimation is linked to available data where:

- DSA prospects are described using public data and public references. The level of maturity is low. Key data is missing in many regions as seismic surveys and/or petrophysics data.

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- DHF prospects are classified as Tiers2, although BSA is not available for some areas as data is confidential.
- The SEF (storage efficiency factor) reflects the level of confidence of storage resources. This coefficient has great impact on storage resources estimate. A conservative approach using a SEF of 2% was applied in regions with low confidence on storage resources classification.

Although storage capacities taken into account in the economic evaluations made in D5.3[7] have a low level of maturity, costs of economic evaluations consider storage resources as bankable or ready to operation. The Table 1 gives an overview of storage costs of economic scenarios developed in D5.3.

[7] Economic Evaluation of CCUS Scenarios in Eight Regions of Southern Europe

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Table 1: Storage/maturity & cost and overall CCUS cost in scenarios described in D5.3

Pays	Region	Scenario	Resource Type	Prospects Name	Total S* capacity	S maturity	Mt CO2 stored	Undiscounted S cost (from D5.3)		Total Undiscounted S cost	€ cost CO2 per tonne		Total € cost CO2 per tonne	Overall undiscounted CCUS cost (from D5.3)		CCUS value chain (€/tCO2 avoided) undiscounted	S costs (%) of total CCS costs
								capex	**opex**		**capex**	**opex**		**capex**	**opex**		
ES	**Ebro Basin**	main	DSA	Reus; Maestrazgo-3; Caspe	166,33	Tiers 2	65,5	172,4	475,6	648,0	2,6	7,3	9,9	4777,0	10760,0	237,2	4,2
PT	**Lusitanian**	main	DSA (onshore)	S. Mamede; Alcobaca	96	Tiers 2	60,5	260,0	640,0	900,0	4,3	10,6	14,9	4635,0	8780,0	221,7	6,7
PT	**Lusitanian**	alternative	DSA (offshore)	Q4-TV1; Q4-S1	263	Tiers 1	60,5	500,0	1500,0	2000,0	8,3	24,8	33,1	5000,0	10000,0	247,9	13,3
FR	**Paris**	main	DSA	Chailan; Grès intermediaire	61,9	Tiers 2	29,8	307,9	730,5	1038,4	10,4	24,6	35,0	673,3	2389,5	102,7	34,1
FR	**Paris**	alternative	DSA	Dogger	165	Tiers 2	29,8	217,3	468,0	685,3	7,3	15,7	23,0	581,5	2126,1	90,8	25,3
FR	**Rhone Valley**	main	DSA	Saint Marie de la Mer; Donnemarie	81,9	Tiers 2	29,5	215,0	265,3	480,3	7,3	9,0	16,3	824,4	2178,0	101,9	16,0
FR	**Rhone Valley**	alternative	DSA	Donnemarie	68,9	Tiers 2	29,5	218,2	263,6	481,8	7,4	9,0	16,4	882,7	1739,1	89,0	18,4
HR	**Northern Croatia**	main	DHF; DSA	Beničanci; Bokšić; Osijek	132,3	Tiers 1	27,2	290,8	715,0	1005,8	10,7	26,3	37,0	624,3	1094,7	63,3	58,5
HR	**Northern Croatia**	alternative	DSA; DHF	Osijek; Drava; Bokšić; Beničanci	2071,3	Tiers 1	28,6	401,9	930,4	1332,3	14,0	32,5	46,5	781,3	1325,1	73,5	63,3

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RO	**Galati**	main	DHF; DSA	SU#01, SU#02, SU#03, SU#04, SU#05	43,3	Tiers 2	37,4	293,9	1126,4	1420,3	7,9	30,1	37,9	1233,5	2453,7	98,5	38,5
RO	**Galati**	alternative	DHF; DSA	SU#01, SU#02, SU#03, SU#04, SU#05	43,3	Tiers 2	28,5	420,0	1294,4	1714,4	14,7	45,4	60,1	1061,6	1979,1	106,6	56,4
GR	**Western Macedonian**	main	DSA		1,15	Tiers 1	7,2	107,7	22,6	130,3	14,9	3,1	18,0	779,6	873,2	228,6	7,9
PL	**Upper Silesia**	main	DSA	SU#03, SU#4	96,2	Tiers 2	85,8	468,3	991,2	1459,5	5,5	11,5	17,0	1643,5	1551,6	37,2	45,7

*S: storage

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Costs of investment (capex) and operation (Opex) of storage are variable among the eight regions with the lower cost in West Macedonia (GR) with 130 M€ and the higher cost in Lusitanian Basin offshore (PT) with 2000 M€. The main difference in storage costs is related to the geological setting of the resource, i.e. offshore resources are more expensive to develop than onshore resources.

Regarding cost per ton of CO_2 stored, the lower value of 15 €/tonne CO_2 stored is in Lusitania Basin onshore (PT) and the higher value of 60 €/tonne CO_2 stored is in Galati region (RO). Costs of CO_2 stored is a function of the total amount of CO_2 to be stored calculated in scenarios of D5.3 between horizon 2025 and 2050. The average price of tonne CO_2 stored is 30 € among the different scenarios elaborated in the eight regions.

2.5.1 Pre - Final Investment Decision (FID) costs

Final Investment Decision covers studies of the initial stages of project development, regulatory approval, permitting of storage and studies in other disciplines as social science. The pre-FID phase of the eight studied region includes the characterisation of the storage complex (including caprock and surround formations) to assess the site's containment, injectivity, capacity, integrity, hydrodynamics, and monitorability in order to ensure safe and permanent storage of CO_2[8].

Data available to characterize the storage complex is heterogeneous among regions. Costly data as active seismic surveys and wellbore data are only available in few regions. These data are essential to the characterization of the storage complex and its monitoring afterwards. Desktop work (modelling, plans, legal documents, etc.) and laboratory/field work (sample measuring, geophysical data, field studies) are also included as costs of the pre-FID phase.

Some regions have two or more prospects in distinct geographic location or geological setting, which increase drastically costs of the storage complex characterization. Seismic surveys and appraisal wells should be designed as function of the geography and geology of storage resource. The investigation of two or more sedimentary formations in different geographic locations is more expensive than the investigation in one given location.

In this section, a first estimation of costs for characterizing storage resources is given for each region. These costs are indicatives and might not represent a realistic price.

2.5.1.1 Ebro (Spain)

Ebro basin main scenario has considered the following components of Pre-FID costs for each storage selected:

- Seismic survey reprocessing costs: 0.5 M€/storage

[8] https://ec.europa.eu/clima/sites/clima/files/lowcarbon/ccs/implementation/docs/gd2_en.pdf

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- Geological model review: Geological, geochemical and geomechanic characterisation of the area from samples, logs and geophysics: 0.5 M€ / storage
- 3D Seismic survey costs: 1.5 M€ / storage
- Dynamic modelling and concept development: 0.5 M€ / storage
- New exploration and appraisal wells (including design, permits and test): 3 wells/storage, 6 M€/well
- Injection testing: 3 existing wellbore/storage, 3 M€/storage
- Risk Framework and MMV plan: 0.3 M€
- Permitting documents (pre FEED[9], EIA[10], investment proposal): 0.7 M€

Total Pre-FID costs for **each** onshore Deep Saline Aquifer storages in Ebro Basin is estimated on 25 **M€.**

2.5.1.2 Lusitanian (Portugal)

The following Pre-FID costs have been estimated for the storage options in the Lusitanian Basin to increase the storage resources maturity from Regional Assessments (Tier 1, offshore units) and Discovery Assessments (Tier 2, onshore units) to bankable resources (at least Tier 3). The main storage scenarios consist of two onshore storage units (SU#1 and SU#2) and the alternative scenarios with one offshore storage unit each (SU#3 and SU#4).

The geological characterisation of the areas is part of the studies carry out in the H2020 PilotSTRATEGY project (No. 101022664)[11] :

- Geological conceptual model: Geological/ mineralogical, geochemical and geomechanical characterisation of the area from samples, logs and geophysics: 0.5 M€/ storage
- 2D/3D seismic data acquisition: 1.4 M€/ storage
- Numerical modelling and sensitivity studies: 0.5 M€/ storage
- Risk Framework and MMV plan: 0.1 M€
- Permitting documents (offshore and onshore): 0.5 M€
- Appraisal injector well (onshore): 12 – 14 M€ well/ storage:
- Appraisal injector well (offshore): 14 – 32 M€ well/ storage:
- Injection testing and formation data acquisition: 1.4 M€/ well

[9] Front End Engineering Design study
[10] Environmental Impact Assessment study
[11] https://pilotstrategy.eu/

[5] The offshore drilling and completion costs were estimated based on reported literature values (e.g., from Kaiser, 2021) for injector wells at similar water depths as those considered in the storage units of Portuguese CCUS scenarios. Reference: Kaiser, M.J. (2021). A Review of Exploration, Development, and Production Cost Offshore Newfoundland. Natural Resources Research, Vol. 30, Nº2. Doi: https://doi.org/10.1007/s11053-020-09784-3.

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Most of the four storage units considered in the scenarios are covered by geophysical data (wells and seismic data). However, acquisition of 2D/3D seismic data would be crucial, mostly in the northern areas of storage units S. Mamede (SU#1) and Q4-S1 (SU#4) where data is very scarce or unavailable, for an accurate reservoir dimensioning and to carry out reservoir numerical modelling studies. Another critical component regards to CO_2 injection tests in each storage unit to improve the insights about injectivity, as well as additional formation data acquisition, namely permeability of reservoir-caprock pairs, formation pressure and reservoir fluid sampling. The costs range of the offshore appraisal wells corresponds to the drilling and completion costs[5] at different depths between the two types of potential reservoirs. Contrasting to the offshore costs, the difference in the costs range for the onshore geological setting is smaller due to the similar reservoir depths of SU#1 and SU#2 as the potential reservoirs are the same (Upper Triassic).

Total Pre-FID costs associated with the main scenario (onshore storage) in Lusitanian Basin (Deep Saline Aquifers) is around **35 M€** (SU#1 + SU#2) and the alternative scenarios (offshore storage) ranges between around **19 M€** and **37 M€** for the shallower (SU#3, Lower Cretaceous) and the deeper (SU#4, Upper Triassic) potential reservoirs, respectively. The higher Pre-FID costs for the onshore storage is due to the deeper reservoirs and by the fact that two storage units are considered in the scenario, contrasting to only one unit for each alternative scenario.

2.5.1.3 Paris (France)

The following components of Pre-FID costs have been estimated for Paris Basin region considered in the alternative scenario. The geological characterisation of the area is part of the studies carry out in the H2020 PilotSTRATEGY project (No. 101022664)[12] :

- Geological conceptual model: Geological, geochemical and geomechanic characterisation of the area from samples, logs and geophysics: 0.7 M€ / storage
- 3D Seismic survey costs: 1.5 M€ / storage
- Modelling and sensitivity studies: 0.8 M€/storage,
- Risk Framework and MMV plan: 0.5 M€
- Permitting documents (pre FEED[13], EIA[14], investment proposal): 0.5 M€
- Injection testing: 1 existing wellbore/storage: 3 M€/well
- Appraisal well: well/storage: 4 M€/well
- Monitoring well: well/storage: 4 M€/well

Total Pre-FID costs for the Dogger onshore storage of alternative scenario in Paris Basina (Deep Saline Aquifer) is around **15 M€**. This costs are also representative of the main scenario concerning the Trias reservoirs.

[12] https://pilotstrategy.eu/
[13] Front End Engineering Design study
[14] Environmental Impact Assessment study

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2.5.1.4 Rhone Valley (France)

Storage option considered in The Rhone Valley scenario is divided in 2 periods: 1st period until 2039 storing CO_2 at vicinity area of sources in the prospect: Saint Marie de La Maire (FR2.SU.003) and; the 2nd period storing CO_2 at Donnemarie prospect (FR1.SU.004) in the Paris Basin.

Paris Basin costs estimated in previous section 2.5.1.3 could be extrapolated to the Donnemarie prospect concerning data and work needed to make a pre FID (Final Investment Decision). It is around 15 M€.

Costs to make a pre-FID in the prospect Saint Marie de La Maire could be similar, although some geographic aspects should impact on cost and acceptability for gathering new data as seismic surveys. The area is located onshore near to the shore face near, to a Natura 2000 area and the Natural Park of Camargue.

Total Pre-FID costs for the Rhone Valley onshore storages options of the main scenario is around **30 M€**.

2.5.1.5 Northern Croatia

The following components of Pre-FID costs have been estimated for Northern Croatia region considered in the main (long-term) scenario:

- Geological conceptual model: Geological, geochemical and geomechanic characterisation of the area from samples, logs and geophysics: 0.5 M€ / storage
- 3D Seismic survey costs: 5 M€ / storage
- Modelling and sensitivity studies: 0.3 M€/storage,
- Risk Framework and MMV plan: 0.2 M€
- Permitting documents: 0.5 M€
- Injection testing (1 existing wellbore/storage): 1.5 M€/well
- Appraisal well (well/storage): 7 M€/well

Total Pre-FID costs for the Northern Croatia onshore storages of the main scenario in the Eastern cluster (Deep Saline Aquifer and 2 Depleted Hydrocarbon Fields) is around 3□(0.5+5+0.3+0.2+0.5) + 2□(injection testing + appraisal well) = 19.5 + 17 = 53.5 M€.

2.5.1.6 Galati (Romania)

Galati area main scenario included the following components of the Pre-Fid study:

- Seismic survey costs: 1 M€/storage
- Geological model review: Geological, geochemical and geomechanic characterisation of the area from samples, logs and geophysics: 0.5 M€ / storage
- 3D Seismic survey costs: 1.5 M€ / storage
- Modelling: 0.5 M€ / storage
- New exploration and appraisal wells (including design, permits and test): 1 well/storage site, 6 M€/well for onshore sites and 10 M€/well for offshore site

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– Permitting: 1 M€

2.5.1.7 Western Macedonian (Greece)

The following Pre-FID costs have been estimated for the Western Macedonia region:

- Geological conceptual model: Geological, geochemical and geomechanic characterisation of the area from samples, logs and geophysics: Offshore DeepWater (Water depth >100 m): 22,633 €/m, Offshore ShallowWater (Water depth <=100 m):: 10,787 €/m, Onshore: 5,938 €/m
- Seismic survey reprocessing costs: 0.4 M€/storage
- 3D Seismic survey costs: 5 M€ / storage
- Modelling and sensitivity studies: 0.4 M€/storage
- Risk Framework and MMV plan: 0.3 M€
- Permitting documents: 0.5 M€
- Injection testing (1 well/storage): 4 M€/well
- Appraisal well (well/storage): 6 M€/well

2.5.1.8 Upper Silesia (Poland)

The following components of Pre-FID costs have been estimated for Upper Silesia:

- Modelling / logging costs: 0.2 M€/storage,
- Seismic survey costs: 0.8 M€/storage,
- Injection testing: 2 wells/storage, 1.5 M€/well
- New exploration wells: 4 wells/storage, 1.2 M€/well
- Permitting: 1.2 M€/storage

Total Pre-FID costs for 2 onshore storages in Upper Silesia (Deep Saline Aquifer Cieszyn-Skoczów and Deep Saline Aquifer Częstochowa) are equal **20.0 M€**.

2.5.2 Discussion

Accordingly to ZEP (2011), the economic impact of activities during storage pre-FID stage represent between from 10% to 75% of storage life cost (Figure 4). When comparing this cost with CCS chain cost, this cost represents only 3-5% of overall CCS cost.

The economic scenarios of STRATEGY CCUS (D5.3) include multiples CO_2 sources from a variety of industrial sectors. Transport network and storage options are complex in some regions combining pipelines and ships (i.e. Ebro Basin). High CCUS chain costs scenarios are those with several (more than 10) emitters such as in Lusitanian Basin and Ebro Basin. Storage costs in these scenarios are low within the total CCUS chain costs; although they have higher storage costs. Storage costs in Lusitanian Basin onshore (PT) is about 7% of total CCUS chain costs whereas it is 63% in North of Croatia region, which has only three medium-small emitters and less than 30 Mt of accumulated CO_2 stored.

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The costs of storage per CO_2 tonne stored (capex + opex) is a function of the quantity of CO_2 been stored with low values for onshore option, as in Upper Silesia. These costs vary from 14 €/tonne of CO_2 stored (Lusitania Basin onshore) to 60 €/tonne of CO_2 stored (Galati region).

Costs to reach a bankability status in these eight regions are the pre-FID (Final Investment Decision) costs. Pre-FID costs estimated in STRATEGY CCUS regions represent between 1% (Galati Region) to 6% (Rhone Valley region) of total storage costs (Capex[15]+Opex[16]), which is less than the expected costs of 10% to 75% estimated by ZEP (2011).

2.6 Actions on CO_2 storage resource investigation

The specificity of CO_2 storage, compared to hydrocarbon exploration, is that it doesn't bring any revenue as hydrocarbon production, and hence it does not yet generally justify risking tens of millions of dollars for a single private company to work on increasing storage capacity.

Facing to this specificity, government can assist by providing support. For example, based on the results from this project, PilotSTRATEGY[17] project was launched in 2021, with objective to provide pre-FEED studies to build storage pilots in the Paris, Lusitanian and Ebro Basins, helping develop confidence in CCS by supporting safe and effective operations. Among other things, the studies will produce the legal documentation which projects need to apply for permits.

Besides government, private companies could work together on the sharing of storage data and cost. For example, in July 2020, the Oil and Gas Climate Initiative (OGCI) launched the CO_2 Storage Resource catalogue, which aims to become the global repository for all future storage resource assessments, supporting the growth of a safe and commercially viable CCUS industry. It will do this by bolstering investors' understanding of commercial development and maturity of published CO_2 storage resources, thereby leading to increased investor confidence.

3 Business models

3.1 Introduction

Latest world map of CCS facilities (Figure 5), extracted from the last update given by Global CCS institute (The Global CCS Institute, 2021), gives a panorama of CCS projects in operation and in development.

[15] Capital Investment costs
[16] Operational costs
[17] https://www.strategyccus.eu/pilotstrategy-project-launch

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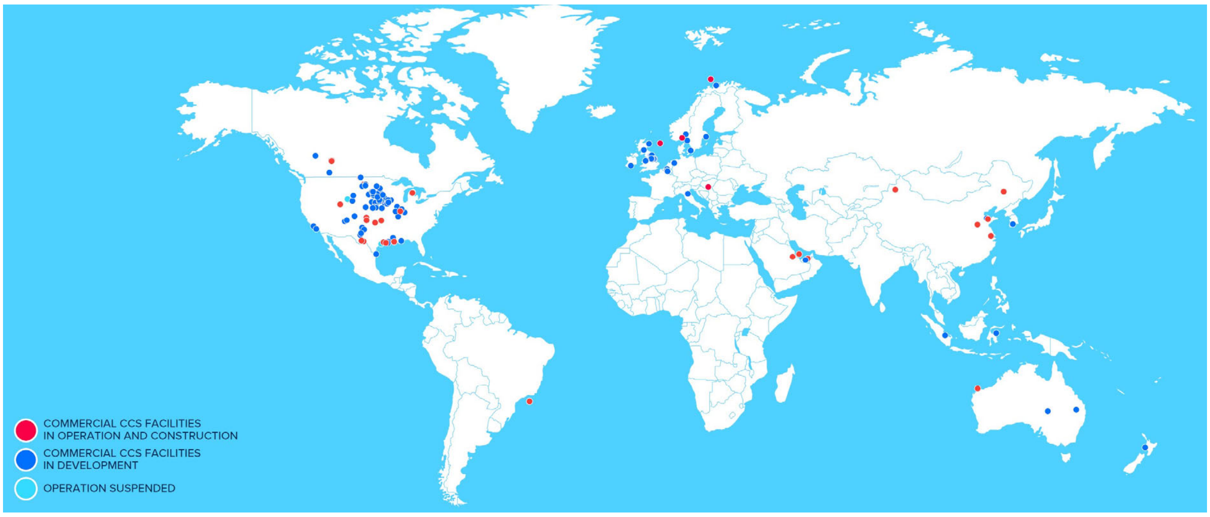

Figure 5: world map of CCS facilities at various stages of development (The Global CCS Institute, 2021)

CCUS projects are emerging and in early phase. It is still far to reach mature and massive deployment and there is no general business model. CCUS projects are seen as "case-by-case". Hence, it is valuable to review what are available policy mechanisms/business models for existing CCUS projects before discussing what are potential business models could be applied in the studied regions.

3.2 Business model elements

Two core elements in a business model are revenue and cost. For CCUS value chain, cost part includes majorly capital investment (CAPEX) and operating expense (OPEX). Key challenge is on revenue part, i.e. value proposition. Moreover, as declared in CCUS business model review carried by (Muslemani, 2019), three other categories should be investigated when establishing CCUS business model: funding source, capital & ownership and risk management (Figure 6).

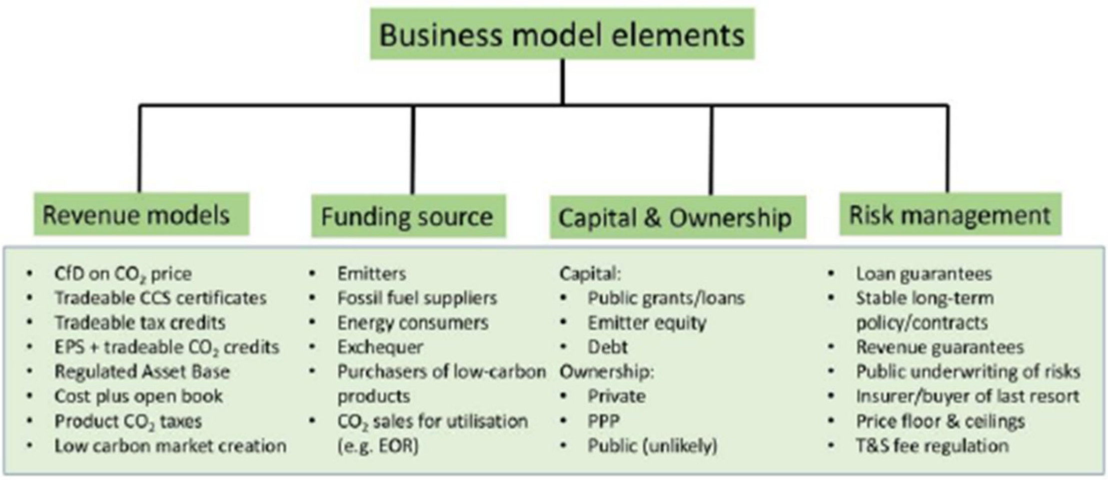

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Figure 6: Business model elements (Muslemani, 2019)

Besides, (Muslemani, 2019) summarized CCS business model case studies. It comes out that most current CCUS projects couldn't live without government funding/policy instruments.

3.3 Available government funding and policy support

IEA report (IEA, 2020) provides a summary table on policy instruments that support CCUS.

Table 2: Main policy instruments for CCUS development and deployment ((IEA, 2020))

Category	Types	Examples
Grant support	Capital funding provided directly to targeted projects or through competitive programmes to overcome high upfront costs.	• UK CCUS infrastructure fund • EU Innovation Fund
Operational subsidies	• Tax credits based on CO_2 captured/stored/used. • Contracts-for-difference (CfD) mechanisms covering the cost differentials between production costs and a market price. • Feed-in tariff mechanisms with long-term contracts with low-carbon electricity producers. • Cost-plus open book mechanisms in which governments reimburse some costs as they are incurred, reducing risk for the contractor	• US 45Q and 48A tax credits • Netherlands' SDE++ scheme • UK power sector CfD arrangements
Carbon pricing	• Carbon taxes, which impose a financial penalty on emissions. • ETSs involving a cap on emissions from large stationary sources and trading of emissions certificates.	• Norway carbon tax on offshore oil and gas • European ETS • Canada federal Output-Based Pricing System
Demand-side measures	• Public procurement of low-CO2 building materials, transport fuels and power, including those produced with CCUS. • Border adjustments, adding a carbon tariff on imported goods to prevent competition from those with higher CO2 and a lower price.	• Canada and the Netherlands rules favouring low-CO2 material inputs for construction projects • Several jurisdictions (including in the US, Canada and EU plan to purchase concrete cured using CO_2)
Regulatory standards and obligations	• Mandates on manufacturers to meet emissions criteria, or oblige firms to purchase a minimum share of products with low lifecycle CO2 emissions. • Regulated asset base, a model for investment recovery through a regulated product price passed on to consumers.	• EU Renewable Energy Directive II • UK energy and infrastructure markets employ a regulated asset base model

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	• Emissions standards establishing limits on unabated CO2 emissions	• Limits on allowable CO2 intensity from coal and natural gas power generation in Canada
Risk mitigation measures	• Loan guarantees covering project developers' debt should they default on loans. • Pain-gain risk-sharing mechanisms whereby partners share some projects risks. • CO2 liability ownership, in which governments take a share of liability for stored CO2, in particular after project closure.	Australian legislation allowing the transfer of CO_2 liability to the state.
Innovation and RD&D	• Funding for RD&D, either directly in state-run research institutions or indirectly through grants and other types of subsidy for private activities. • Competitive approaches to support RD&D for low-carbon technology	• EU Horizon 2020 • US Department of Energy CCUS R&D programmes

More details are given below in order to illustrate the amount of financial support from government.

3.3.1 US

The US Energy Act of 2020 (11) passed in December 2020 as part of the Stimulus Bill. More than 6 billion$ was authorised for CCS research, development, and demonstration programs in the DOE and Environmental Protection Agency (EPA) for FY 21 – FY 25, including: 2.6 billion$ for commercial-scale demonstrations, 1 billion$ for large-scale pilot projects, 910 million$ for DOE low-TRL level R&D, 800 million$ for a large-scale carbon storage and validation program, 200 million$ for FEED studies, and more than US$1 billion for other activities (The Global CCS Institute, 2021).

Besides funding support, legislations are under discussion. A tax credit known as Section 45Q, named after the relevant section of the US tax code, was expanded in 2018, providing a significant boost to CCUS investment plans. It now provides a credit of up to USD 50/tCO2 for permanent geological storage, or up to USD 35/t for EOR or other beneficial uses of CO2. The credits are slated to last for 12 years for projects started within a specified period; to be eligible for the credit, a construction on a new project would need to begin by 1 January 2024. The value of these credits is adjusted over time to take account of inflation. The conditions for projects to qualify for the credit was changed to allow for smaller sources of CO2 and a cap on the total credit available was removed.

In January 2019, a CCUS protocol was agreed under the Californian LCFS, which allows transport fuels whose life-cycle emissions have been reduced through CCUS to become eligible for additional tax credits. Facilities anywhere in the world capturing CO2 through DAC for permanent geological storage and projects that produce ethanol for sale in California and store the CO2 (including through EOR) are

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also eligible for credits but must satisfy the requirements of the LCFS CCUS protocol (which includes monitoring for 100 years). The value of these credits, which are tradeable, has risen to more than USD 190/tCO2 in Q3 2020 (IEA, 2020).

3.3.2 EU

The European Union made climate neutrality by 2050 a legally binding target, along with reducing 2030 net GHG emissions at least 55%, compared to 1990 levels.

Recent policy measures include the EU Innovation Fund, which makes available up to EUR 10 billion (USD 11.9 billion) to support the demonstration of low-carbon innovative technologies, and the EU Horizon 2020 (EUR 70.2 billion/ USD 83 billion) dedicated to research and innovation covering a number of topics including energy system decarbonisation. National policies include the Dutch SDE++ programme – an operating grant intended to support the deployment of sustainable energy and CO2 reducing technologies and practices – and CCUS funding in the United Kingdom.

The UK government announced the establishment of a CCS Infrastructure Fund of at least GBP 800 million (USD 1 billion) to support CCUS in at least two sites, one by 2025 and one by 2030 (UK Government, 2020).

In December 2020, the Norwegian Government decided to invest in full chain CCS-longship project, with a share of NOK 16.8 billion NOK (1.9 billion$), in a total cost estimate of 25.1 billion NOK (2.8 billion$)[18].

3.3.3 Ebro (Spain)

Currently there is not available national funding specifically for the development of CO2 geological storage demonstration projects in Spain but those projects could be funded by more general national of co-funded programs.

The State Plan for Scientific, Technical and Innovation Research 2021-2023 is the instrument that allows to develop, finance and execute the public policies of the General Administration of the State in terms of promotion and coordination of R&D. The Plan is articulated through four state programs that are developed through subprograms with specific objectives and that include state, annual and multiannual public aid, dedicated to R & D + I activities. One of these subprogramme includes, among other actions, Science and Innovation Missions, which are pre-competitive research projects, led by companies that pursue relevant research that propose solutions to transversal and strategic challenges of Spanish society, improve the knowledge and technology base on which Spanish companies rely to compete, while stimulating public-private cooperation. Other programs also valid for CCUS project are, for example, CDTI-Era-Net or EUREKA. The Center for Industrial Technological Development (CDTI) is the main responsible of them.

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[18] https://www.regjeringen.no/en/topics/energy/landingssider/ny-side/sporsmal-og-svar-om-langskip-prosjektet/id2863902/?expand=factbox2864130

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3.3.4 Lusitanian (Portugal)

There is no national funding programme specifically dedicated to CCUS.

In principle the Recovery Plan can be utilised to fund CCUS projects, but in practice it is difficult to implement it, since the funds must be spent, with a clear economic or environmental return until 2026, given the low level of maturity of the storage component.

The Environmental Fund (Fundo Ambiental) provides funding for low carbon projects, but unlikely to be able to fund pilot or industrial scale projects.

Funds for research projects under 200 k€ can be obtained through the competitive calls of the National Foundation for Science and Technology (FCT).

3.3.5 Paris & Rhone Valley (France)

Extrait from Duscha, 2022 (D6.1 - Regulatory framework for CCUS in the EU and its Member States, PilotSTRATEGY deliverable[19])

Different sources can be accessed for the support of CCS projects (ADEME 2019). Projects in the R&D phase can find national financial support either via the ADEME thesis program, a program designed to support students in writing a phD thesis, or via specific calls for R&D projects. Investments into demonstration projects and for further industrial development can be accessed via the Investments for the future program. The program as a whole has a budget of 57 billion €, of which 4 billion € are available for funding of projects for the environment and in the renewable energies sector. This part is operated by ADEME. There are two support possibilities: via state ‑ aid combining grants and refundable loans (up to 2.8 billion € are spent that way) or via capital investments by ADEME in the form of co ‑ investments either with corporates or financial partners in project companies or with venture funds in SME's companies. For the later part 1.2 billion € are available. A broad spectrum of projects can be funded under the Investments for the future program including renewable energy projects, environmentally friendly buildings, green chemistry, energy storage, hydrogen production, water and biodiversity, waste and industrial ecology projects, polluted site remediation and projects in the area of transport for the future. Specific funding programs focusing on CCU or CCS activities were not identified.

3.3.6 Northern Croatia

Currently there are not available national funding opportunities specifically for the development of CO2 geological storage demonstration projects in Croatia. However, the Innovation fund supports low-carbon projects. The National Recovery Plan generally includes CO2 injection pilot projects if they are connected with other low-carbon projects such as biorefinery in Sisak, and improvement of process in a fertilizer company (Petrokemija). Injection of CO2 will be supported if there is no

[19] https://pilotstrategy.eu/about-the-project/work-packages/social-acceptance

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increase in hydrocarbon production at respective sites. Additionally, the revenues from EU ETS are directed to low-carbon technologies but not CCS.

3.3.7 Galati (Romania)

At the moment, there is no dedicated national funding to CCS. Low-carbon projects still can benefit from financing from the Ministry of Environment and Forests (renewable projects) and from the Ministry of Energy.

The CO2 emitters from Romania can also apply to the Modernisation Fund, coordinated through the Ministry of Energy. This fund finances investments in the priority sectors identified by the Ministry based on national strategies and objectives at European level. The mechanism for allocating the available funds from the Modernization Fund is implemented through the key programs formulated on the basis of priority sectors. One of the programs is called Energy Efficiency in Industrial Facilities included in the EU-ETS. This program offers support to apply CCS or CCUS for to industrial facilities from the steel, cement, oil and gas, energy production and other highly polluting industries.

The National Recovery and Resilience Plan for Romania, approved by the European Council, has an allocation of 29.2 billion EUROs. For the energy sector, the allocation is of 1600 million EUROs and refers to electric energy production from renewable sources, development of a regulatory framework for future energies (mainly referring to hydrogen), building the distribution infrastructure for gases from renewable sources, development of new capacities for gas production, building capacities for production of photovoltaic panels and assuring the energy efficiency in the industrial sector. No reference to CCS is made.

Apart from this, research projects related to CCS can benefit from funds from the national program for research financed by the Ministry of Research and Digitalization. The last program ended last year and a new program is soon to be released. In the past, there was also a competition for the Norwegian funds for research, through the bilateral program Romania-Norway.

3.3.8 Western Macedonian (Greece)

Greece does not have a special CCUS national funding. The main body of the country that allocates resources from environmental taxes, environmental damage fees, etc., to environmental conservation programs is the Green Fund. It is a Legal Entity under Public Law and its purpose is to enhance development through environmental protection by managing, financially, technically and financially supporting programs, measures, interventions and actions aimed at promoting and rehabilitating the environment and supporting the country's environmental policy.

The total capital needs of Greece's energy transition are estimated at €19.1 billion. During the first phase of the period 2021-2030, it is estimated that annual investments of €8.5 billion will be required, mainly for the development and storage of RES, the upgrade of networks and the improvement of energy efficiency. During the second phase of the period from 2030 to 2050, the needs rise to €10.6 billion per year, with the transport sector as the significant recipient.

3.3.9 Upper Silesia (Poland)

Currently, there is no national funding dedicated to CCUS operating in Poland. However, it is possible to obtain funding for low carbon projects. Currently, it is possible to obtain only domestic funds offered by:

- National Fund for Environmental Protection and Water Management
- Voivodeship Funds for Environmental Protection and Water Management

Co-financing from these funds (loans and grants) can be obtained for the following types of projects related to reduction of CO_2 emission:

- Zero-emission energy systems.
- Clean Air: co-financing for the replacement of the old stove and house insulation.
- Reducing the negative impact of enterprises on the environment, including the improvement of air quality by supporting investment projects.
- My Electricity: purchase and installation of photovoltaic micro-installations.
- Development of the electricity infrastructure for the development of electric vehicle charging stations.
- Reducing dust and gas emissions, including the "Low emission", increasing the energy efficiency of generation, transmission or use of energy.
- Promotion of renewable or alternative energy sources.

These funds finance the preparation costs (technical and design documentation) and capital expenditures. The budgets of these funds are different each year. For example, in 2022, the National Fund for Environmental Protection and Water Management wants to allocate 440 M€ to the "Clean Air" program, and 150 M€ to "My Electricity".

Probably from 2023 it will also be possible to obtain European Union funds for low carbon projects. The rules and scope of granting these funds, as well as the budget, are currently unknown.

3.4 Ownership types in CCUS chain

CCUS value chain is a long value chain and covers several sectors: CO_2 emitters, transporter, and CO_2 storage operators. CO2 emitters are heavy industries and power industries (such as power plant, cement plant, steel plant, fertilizer plant, etc), CO2 storage operators are generally oil & gas company, while CO2 transporters can be pipeline companies, or shipping companies.

From literature, three business models are identified to contractually organise projects.

3.4.1 Vertically-integrated CCUS business model

This business model means one single company operates CCS chain (Yao, 2018). The revenue generated in this model includes:

- Direct subsidy for CO2 storage from the government
- Revenue from oil sales generated by EOR
- Revenue from selling extra carbon emission credits in the carbon trading market.

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China's Yanchang demonstration project and Sinopec's shengli Power plant use this model. This model decreases the risks associated with difficulties in cooperation among different sectors, but it limits number of companies that can enter into the market and operate entire CCUS industry chain.

3.4.2 Joint venture CCUS business model

This business model involves cooperation among different sector. In this model, CO2 is captured from an emitter plant owned by a third party, where CO2 is transported to a storage/EOR site, also owned by a third party. A typical JV ownership structure can be 40% (emitter company), 30% (transport company) and 30% (oil company) (Yao, 2018).

Quest CCS project uses this model.

3.4.3 CCS operator business model

In this model, it includes CCS operator, CO2 emitter company and oil company (only in case of EOR). In this model, CCS operator bears cost of capture, transport and storage, and in case where EOR exists, oil company bears cost of EOR and CO2 purchasing from CCS operator. CO2 emitter company generates no profit but produce a low-carbon product; CCS operator generates revenue in the form of a direct subsidy from government for CO2 storage and revenue from oil company for CO2 sale.

US Enid fertiliser EOR project and Canada's Weyburn-Midale project use this business model.

3.4.4 CCUS transport business model

In this model, it includes CCS emitter, CO2 transport company, and oil company. CO2 emitter covers CO2 capture cost, CO2 transport company covers CO2 transport cost and oil company covers CO2 storage/EOR cost.

Val Verde Natural gas plant and Shut Greek Project use this business model

3.4.5 Combination of different types of models

More business model could be made based on the combination of above models. For example, in the longship project in Norway, CO2 emitter covers CO2 capture cost, while a JV model (northern light company created among Equinor, Shell and TotalEnergies) covers CO_2 transport and storage cost.

3.4.6 Business model discussion in studied region

There is no business model applied for all projects, as it depends on local political mechanisms and market size. Based on the literature review in precedent sessions, it seems that vertically-integrated CCUS business model cannot be applied in EU context as it requires a high investment and has a high associated risk. The best suitable business model considered in the studied region would be risk-shared ownership type, i.e. a JV model and/or a transport business model:

- CO_2 capture covered by CO_2 emitter or by a group of CO_2 emitters, and driven by development of a low-carbon product, and/or regulation on GHG emission at plant.

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- CO_2 transport and storage can be covered jointly by the same company as service provider, or by two different company with two service contracts. Business is driven as a service of transporting/storing CO_2.
- For CO_2 utilisation, it could be also driven by the market acceptance of CO_2 conversion products.

In this way, risk is shared along the value chain, and it allow more companies in the market and encourage cooperation among companies in different sectors.

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4 Conclusion

The results show that, all storage sites in studied regions haven't reached bankability status. The deployment time of increasing storage site maturity to bankability status may take between 5 to 10 years, depending on the current maturity and exploration loops. This finding suggests the necessity to carry out relevant work from today. The cost repartition along storage life cycle indicates that the cost in exploration part represents < 6% of the storage life costs in the STRATEGY CCUS regions. The costs of storage per CO_2 tonne stored (capex + opex) is a function of the quantity of CO_2 been stored with low values for onshore option, as in Upper Silesia.

Governments and private company alliances seem to be the key financial support providers. In all regions is missing political support with funding to finance CCUS, especially for storage characterization.

Concerning the revenue models, today, most existing CCS projects receive policy supports. There are various supports (European levels or national levels), and in various forms (subsidy, specific contracts, etc). National funding opportunities exist as well, even not specific for CCUS projects. In the longer term, these supports are believed to evolute together with EU ETS system to ensure business profitability.

CCUS is a long value chain, involves many sectors (power, cement, steel, refinery, oil & gas, shipping, pipeline, etc) and hence various ownership models have been discussed (from vertically-integrated, to operator business models). It is recommended to segment CCS chain into 2 parts (CO2 capture, and CO2 transport/storage) or 3 parts (CO2 capture, CO2 transport, and CO2 storage), in order to bring down market entrance barrier and allow more companies to participate in the market. Then for each part, Joint-Venture model is recommended in order to further share risks and accelerate development.

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