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Economic Evaluation of Eight Regional Scenarios for the Deployment of Carbon Capture, Use and Storage in Southern and Eastern Europe to 2050

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Abstract

During the three-year EU-funded STRATEGY CCUS project [1] [3] (2019-2022), Carbon Capture, Use and Storage (CCUS) scenarios formulated for eight regions in Southern and Eastern Europe were developed and economically evaluated up to 2050. These regional CCUS scenarios are based on both the performances of local industries in operation and for which CCUS is a relevant mitigation alternative, as well as the regional storage capacities known to date. The eight CCUS regional scenarios are in: 1) Paris basin and 2) Rhône Valley in France, 3) Ebro basin in Spain, 4) Lusitanian basin in Portugal, 5) Northern Croatia, 6) Upper Silesia in Poland, 7) West Macedonian area in Greece and 8) Galati area in Romania. They cover an extensive and original portfolio of possible CCUS business models.

While some scenarios assume that the captured CO2 is used for synthetic methane or chemical production, in most cases the captured CO_2 is sent to CO_2 storage facilities. The biogenic CO_2 captured is monitored and its storage time in new uses watched. The economic evaluation considers the negative CO_2 emissions resulting from the long-term storage or use of captured biogenic CO_2.

This paper compares the economic Key Performance Indicators (KPIs) of these eight CCUS business cases with the carbon penalties that would have been charged to the same industries to remain in compliance with the European Union - Emissions

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Trading System (EU ETS). The calculated KPIs mainly reflect the costs and revenues expressed in euros per ton of CO_2 avoided or removed for the whole regional scenario until 2050

Keywords: CCUS; cluster; hub; techno-economic evaluation; CO_2 *value chain; biogenic* CO_2 *; EU ETS; business model; Europe; scenario;negative emissions*

1. Introduction

During the STRATEGY CCUS project a series of Carbon Capture Use and Storage (CCUS) scenarios formulated for eight Southern and Eastern European regions were developed and techno-economically assessed up to 2050 [3].

Eight regional Carbon Capture Use and Storage (CCUS) scenarios are in: Ebro basin in Spain, Lusitanian basin in Portugal, Paris basin and Rhône valley in France, Northern Croatia, Galati region in Romania, Western Macedonia in Greece, and Upper Silesia in Poland.

For each of the eight regional scenarios, several economic Key Performance Indicators (KPI), including the cost difference between investing in CCUS all along the 25 years up to 2050 or paying the carbon penalties to remain in compliance with the EU ETS is calculated, leading to an estimate of the breakeven price of CO_2 for each of the scenarios deployed.

The main goal of this paper is to present the methodological approach used in the techno-economic evaluation of the regional scenarios, followed by an overview and a synthesis of the main results.

2. Methodology used for the techno-economic evaluation of the scenarios

For each region, the scenarios evaluated explore how the deployment of CCUS in such a region might look like from 2025 until 2050. For each of the regional scenarios, the same set of KPIs is provided, making it easy to compare the regional scenarios with each other. Capital and operating costs (CAPEX and OPEX respectively) are annualized and discounted over the lifetime of the scenarios. The additional energy required for operating the CCUS is accounted for, as well as the associated CO_2 emissions (remaining emissions after capture, indirect emissions from electricity use). The CO_2 used as feedstock to produce e-fuels or chemicals or used in mineralization is sold at the EU ETS scenario price (Table 1) and thus generates revenues at a regional scale. No further costs or revenues regarding CO_2 utilization (e.g., investment, product sales) are considered. In addition, the economic evaluation differentiates biogenic-CO_2 (bioCO_2) from fossil-CO_2 emissions, leading in case of permanent storage or long-term use (i.e., mineralization) of bioCO_2 to negative CO_2 emissions.

The CAPEX and OPEX for CO_2 transport are calculated according to the mode of transport used. Pipeline transport considers the topography and land use of the areas crossed, and the pumping energy requirements, including intermediate boosting stations, are calculated based on distance and elevation of the terrain. In the case of CO_2 transport by ship or train, the size of the ships or the number of rail cars needed to transport the CO_2 flow are estimated and optimized.

For CO_2 storage, the CAPEX and OPEX are calculated according to the type of storage envisaged (oil / gas reservoir, depleted oil / gas field or saline aquifer for example) and the number of injection wells required to inject the CO_2 stream. An additional injection well is considered to prevent any risk of injection rupture and a monitoring well is also accounted in the investments as described in “A techno-economic Analysis Tool for Regional CO_2 Capture, Transport, Use and Storage Scenarios” [3].

The main objective of this techno-economic evaluation is to compare (1) the total costs that would result from investing in CCUS on a regional scale with (2) the estimated EU ETS compliance costs (without CCUS) in the same time scale. The main KPIs evaluated for each regional scenario are as follows:

- the volume of CO_2 avoided, used, removed, and stored,
- CAPEX and OPEX per process of the CCUS chain (capture, transport, and storage - in €/t CO_2 avoided),
- the revenues provided by the sales of CO_2 for further utilization i.e. transformation into e-fuels, minerals, or chemical products,
- the average yearly energy needs to implement CCUS in the region,

- the share of CO_2 emission reductions from the CCUS scenarios in the 2050 zero emissions national target.

2.1. General economic data

The economic evaluation is carried out on regional scenarios, i.e., including all the emitters concerned by the capture technology in the region, the modes of CO_2 transport planned for this purpose, the different CO_2 usages if any in the scenario, and the mobilization of different storage sites depending on the volume of CO_2 to be stored.

The capture, transport and storage CAPEX and OPEX used in the economic evaluation are taken from the literature [see 6. Bibliography] and are scaled for the different industries concerned. CAPEX are annualized and a Learning Factor Reduction Costs of -1% per year is applied for the CO2 capture costs.

To ensure a homogeneous comparison between regions, common economic values used in the economic assessment are fixed for all the regions (Table 1). On the other side, and to consider the specificities inherent to the regions, certain very regional techno-economic values are adjusted to the region such as the carbon intensity of electricity consumed or the electricity price.

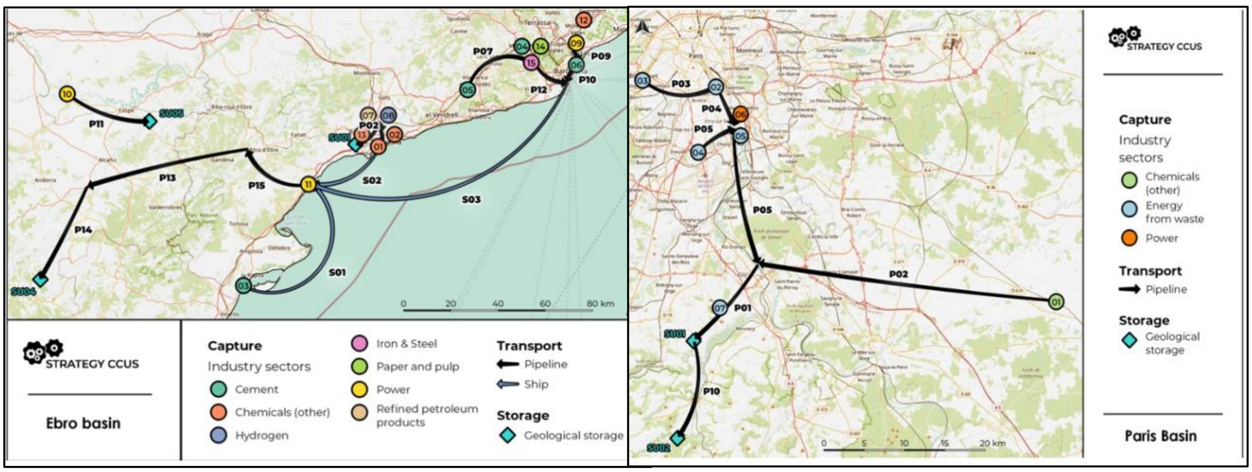
Table 1. Common economic data used in the evaluation of regional scenarios

Common economic data	Value	unit
Price reference year	2021	year
Discount rate	5	%
Inflation rate	2,5	%/year
Learning reduction cost factor for capture	-1	%/year
European Union Allowance on EU-ETS price (yearly average): MEDIUM scenario:		
In 2025 and 2045	70 and 212	€/t CO_2

Costs provided in the assessment are expressed in euros per ton of CO_2 avoided, where CO_2 avoided is the sum of CO_2 stored and long-term CO_2 used.

3. Overview of the eight regional CCUS scenarios results

Before presenting the technical and economic results of the scenarios, a graphic overview of the eight CCUS scenarios is provided (Fig.1).



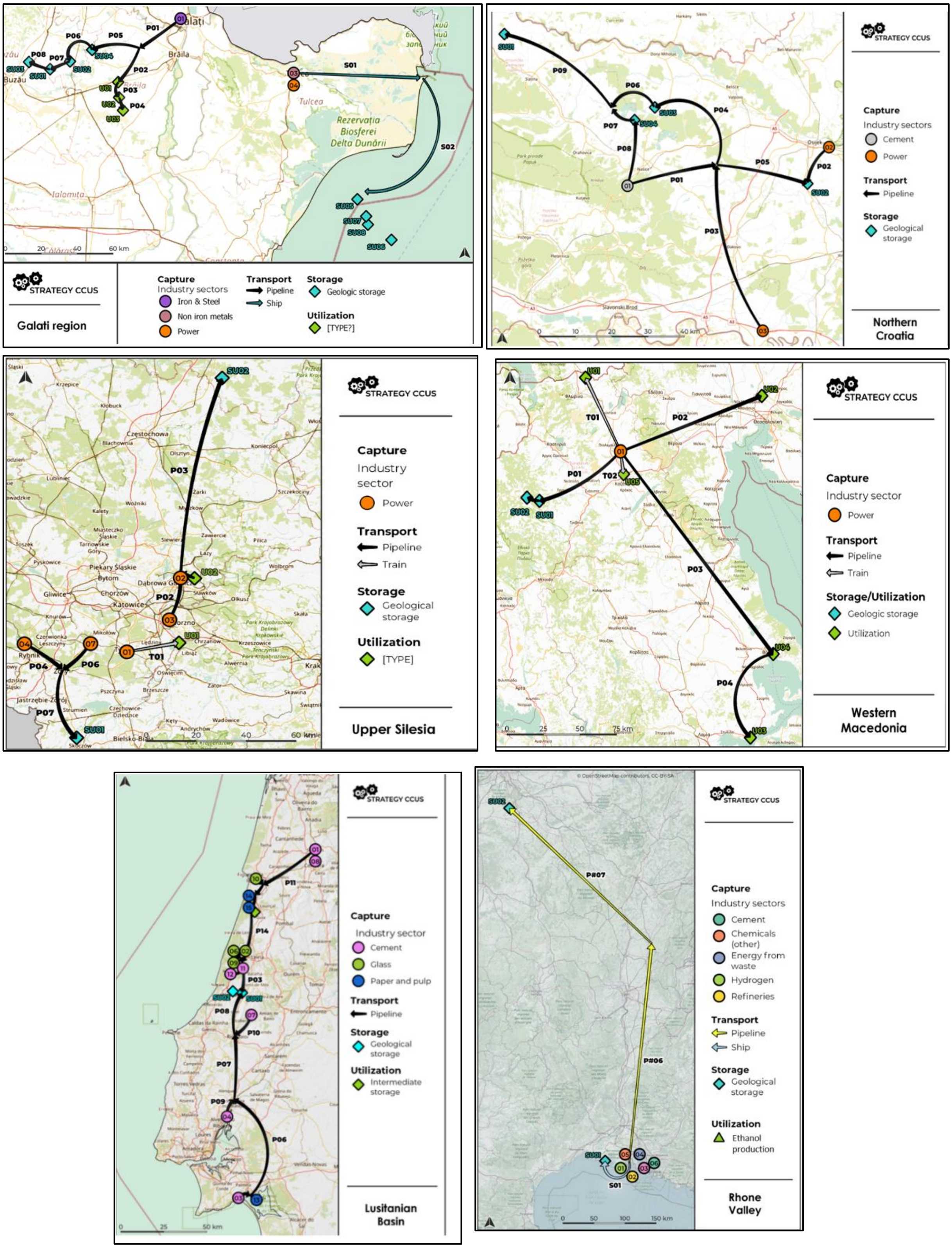


Fig. 1. Graphical summary of the eight CCUS scenarios (a) Ebro basin; (b) Paris basin; (c) Galati region; (d) Northern Croatia; (e) Upper

Silesia; (f) Western Macedonia; (g) Lusitanian basin; (h) Rhône Valley

3.1. Screenshot of the eight CCUS scenarios until 2050

In the eight regions studied, CCUS scenarios lead to a total of 457 Mt CO_2 captured up to 2050, leading to 357 MtCO_2 avoided. For comparison, 1055 Mt CO_2e was emitted in 2018, with France, Poland, Spain accounting for 80% of GHG emissions in the 8 regions. In 2018, Spanish CO_2 emissions represented 349.8 MtCO_2e. These eight regions use 23.8% (109 Mt CO_2) of the CO_2 captured as feedstock in the production of e-fuels, chemicals or in mineralization process. Considering 1% of CO_2 losses all along transport and storage steps, nearly 343 Mt CO_2 are thus geological stored. Once CO_2 used in the production of fast-moving consumer goods (such as fuels or chemicals) is released into the atmosphere, nearly 78% of the CO_2 captured is ultimately avoided. The amount of CO_2 avoided (357 Mt) is greater than that stored (343 Mt) due to the long-term use of CO_2 in mineralization (West Macedonia and Ebro Basin) (Fig. 2).

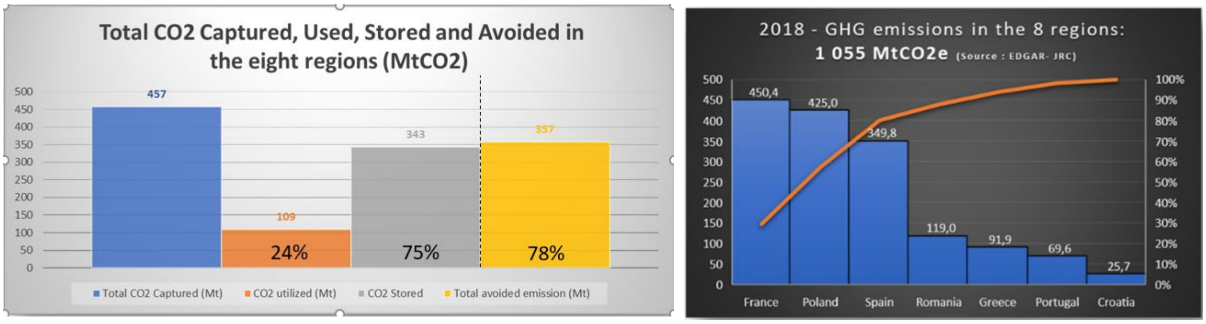


Fig. 2. (a) Total CO_2 Captured, Used, Stored, and avoided in the total of the eight regions: (b) 2018 GHG emissions in Strategy CCUS regions

At the regional level, the 457 Mt CO_2 captured are mainly from Upper Silesia (100.5 Mt CO_2), Lusitanian Basin (93 Mt CO_2) and Ebro Basin (69.4 Mt CO_2) (Fig. 3).

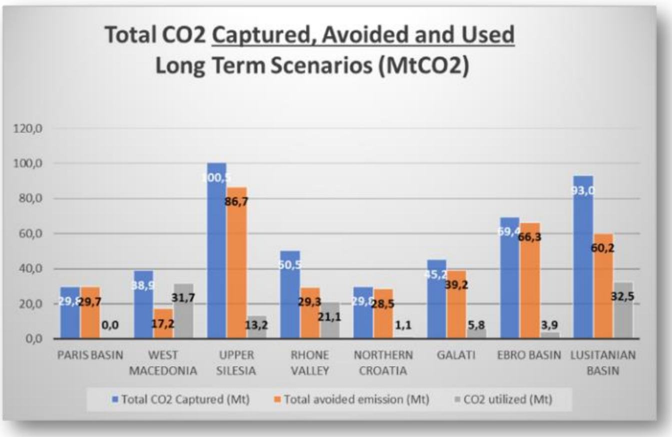


Fig. 3. Total CO_2 Captured, Used, and Avoided in each of the eight regions

3.2. BioCO_2 used in the eight regional CCUS scenarios

Among the total amount of 109 Mt CO_2 used in the regional scenarios, Lusitanian Basin uses 32.3 Mt BioCO_2 in methanation production leading to avoided emissions. In Paris Basin scenario 9.1 Mt of bioCO_2 captured are stored leading to negative emissions. In Rhône Valley 2.2 Mt bioCO_2 captured are stored leading to negative emissions. In West Macedonia 10 Mt CO_2 (fossil CO_2) are used in mineralization leading to avoided emissions. In Ebro Basin 1.1

Mt CO_2 (of which 1.0 Mt bioCO_2) used in mineralization (negative emissions for its bioCO_2 part and avoided emissions for its fossil CO_2 part) (Fig 4).

When captured bioCO_2 is stored in geological reservoirs or used in long-lived products such as mineralization, it could be considered as negative CO_2 emissions. On the other hand, when the captured bioCO_2 is used in short-lived products such as fuels, their combustion releasing CO_2 could be considered as avoided emissions (Fig.4) once there are preventing the emissions from fossil fuels. Additional LCA-based analyses are needed to assess the net CO_2 emissions avoided or removed which has been realized in StrategyCCUS project [4].

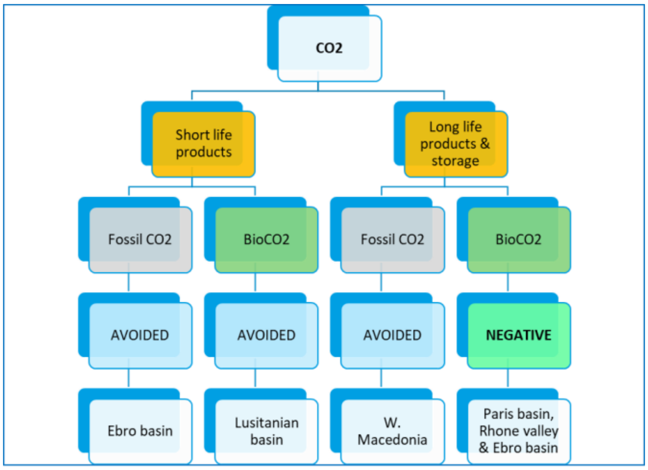


Fig. 4. bioCO_2 use or storage and negative emissions

3.3. Eight regional CCUS total costs

In the eight regions, total costs of 17 389 M€ are estimated for the deployment of the CCUS scenarios. The three regions accounting for the largest share of these investment costs are: (1) the Ebro Basin with 6 150 M€, followed by (2) the Lusitanian Basin with 4 333 M€, and (3) the Galati region with 1 643 M€, (Fig 5). In average and considering annualized costs up to 2050, OPEX account for 63% of total CCUS costs.

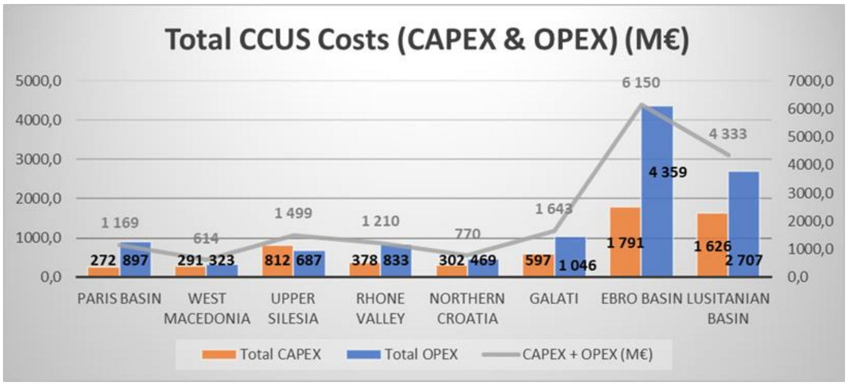


Figure 5. Total CCUS costs in the eight regions

3.4. Costs of CO_2 captured in the eight regions

Among the eight regions, capture costs vary widely from 8€/t CO_2 avoided in Upper Silesia (due to the high amount of CO_2 avoided - 86.7 Mt CO_2 avoided – from power plants) to 64.5 €/t CO_2 avoided in Lusitanian Basin (due to higher capture costs on cement, lime, glass and pulp and paper industries) (Fig 6). These values reflect costs expressed in €/t CO_2 avoided, with a learning curve (-1 % per year) of capture costs, and a total amount of CO_2 captured for 25 years. Capture costs for most industries other than power plants tend to be higher, which has a significant impact on the costs of the entire CCUS chain (capture costs generally represent the larger portion of total costs).

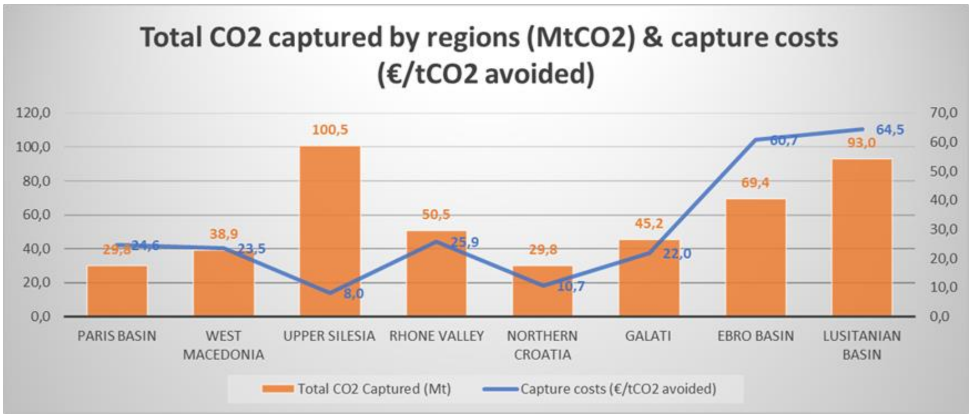


Figure 6. Total CO_2 captured and capture costs in the eight regions

3.5. Total CO_2 transported and transport costs by region

A total amount of 431 Mt CO_2 is fed into different transport modes i.e., pipelines, trains, trucks, or ships and distributed through the network at annual basis.

Among the eight regions, transport costs vary widely from the lowest cost of 1 €/tCO_2 avoided in Paris Basin to the highest cost of 26.9 €/tCO_2 avoided in Ebro Basin, the latter due to the complex and long transport network based upon ships, pipeline, and trucks.

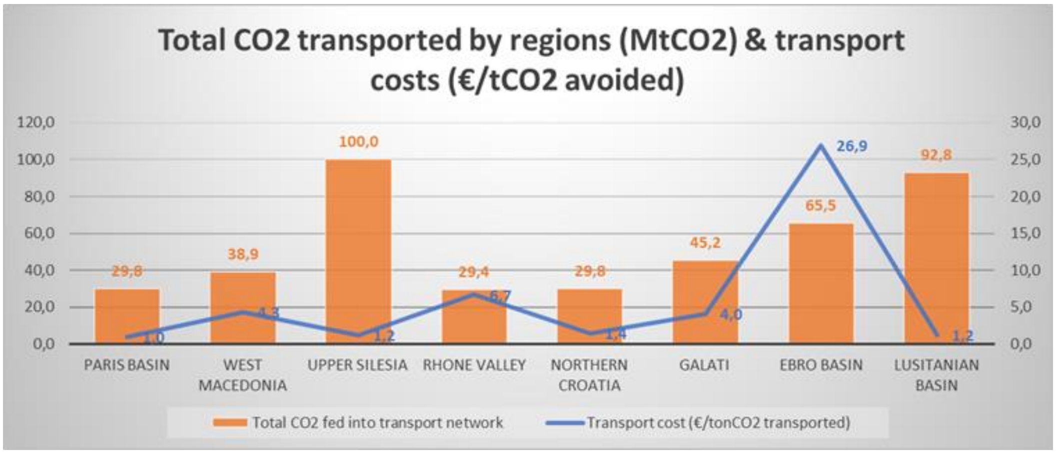


Figure 7. Total CO_2 transported and transport costs in the eight regions

3.6. Total CO_2 stored and storage costs by region

Among the 345 Mt CO_2 stored in the eight regions, the three regions with the most important volumes of CO_2 stored are: (1) Upper Silesia (85.8 Mt CO_2), (2) Ebro Basin (65.5 Mt CO_2) and (3) Lusitanian Basin (60.5 Mt CO_2) (Fig 8).

The storage costs vary from 2.6 €/t CO_2 avoided in West Macedonia up to 15.3 €/t CO_2 avoided in Galati region. The Galati region and northern Croatia have high storage costs due to enhanced oil recovery (EOR) operated before CO_2 is stored later in the scenario.

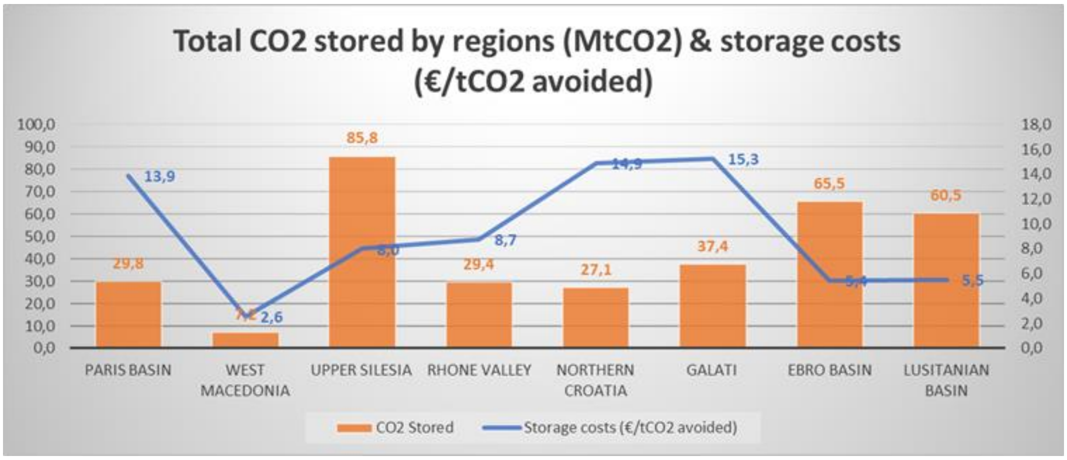


Figure 8. Total CO_2 stored by regions & storage costs

3.7. CCUS costs per tons of CO_2 avoided in the eight regions

For the regions the CCUS value chain ranges from 17 €/tCO_2 avoided in Upper Silesia to 92.8 €/tCO_2 avoided in Ebro Basin. This ratio illustrates the costs per ton of CO_2 avoided over the 25 years of the scenario. The three regions with the highest total investment costs (M€ discounted) are: (1) Ebro Basin (6 150 M€), (2) Lusitanian Basin (4 333 M€), (3) and Galati (1 643 M€). Expressed in euros per ton of CO_2 avoided the same three regions have also the highest costs: (1) Ebro Basin (92.8 €/tCO_2 avoided), (2) Lusitanian basin (72 €/tCO_2 avoided) and Galati region (41.9 €/tCO_2 avoided) (Fig 9).

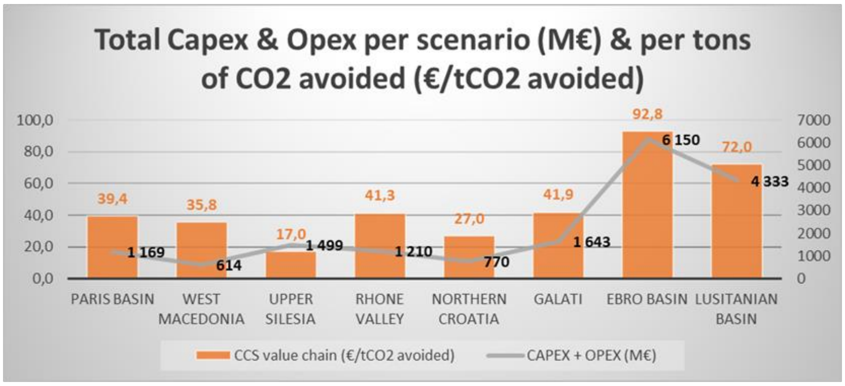


Figure 9. Total Capex/Opex per ton of CO_2 avoided (€/tCO_2 avoided) and per scenario (M€ discounted)

3.8. Total revenues generated by CO_2 utilization

Related to the 109 Mt CO_2 used and sold, seven regions among eight generate a total revenue of 11 336 M€ (discounted): (1) Lusitanian Basin (3 876 M€), (2) West Macedonia (2 841.2 M€) and (3) Rhône Valley (2 146 M€) generate the biggest values (Fig. 10). The CO_2 sale price is considered equivalent to the EU ETS market price scenario of the study (i.e., from 70 €/tCO_2 in 2025 to 212 €/tCO_2 in 2045) (Fig 10).

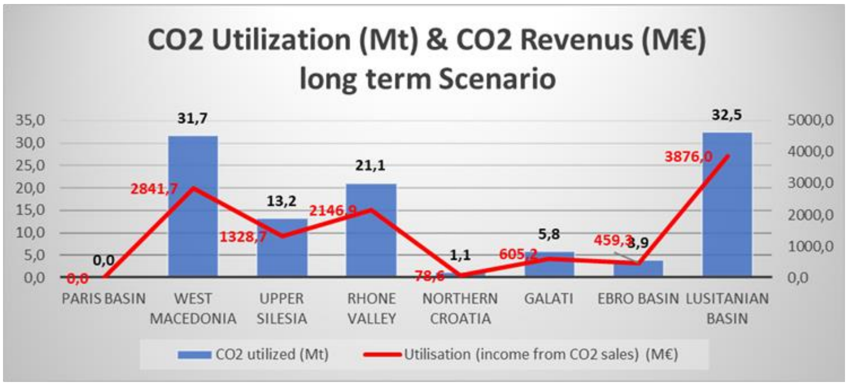


Figure 10. Total CO_2 used, and total revenues associated

3.9. CCUS costs versus EU ETS avoided costs

One of the objectives of the techno-economic evaluation of the CCUS scenarios is to determine whether there is a financial incentive (or not) to invest in CCUS relative to the costs of compliance with the EU ETS, at least with what is anticipated in the future. One way to do this is to compare the total cost of CCUS to the total costs of compliance with the EU ETS and analyze the difference between the two (Fig 11).

Of the eight regions evaluated, the top three regions where CCUS is more attractive than EU ETS compliance are (1) Upper Silesia (4 302 M€ of lower costs with CCUS compared to EU ETS costs), followed by (2) Paris Basin (1 411.9 M€), and then Northern Croatia (with 1 109.5 M€ of financial gap). However, for the Paris basin, this comparison is a theoretical and exploratory exercise, as it includes the incinerators in the EU ETS which is not the case nowadays in France.

In Ebro Basin and Lusitanian Basin, according to this model, it is financially more attractive to pay the EU ETS compliance costs than to invest in the CCUS. But from an environmental point of view the Ebro Basin and the Lusitanian Basin allow to avoid 66.3 and 60.2 $MtCO_2$ respectively.

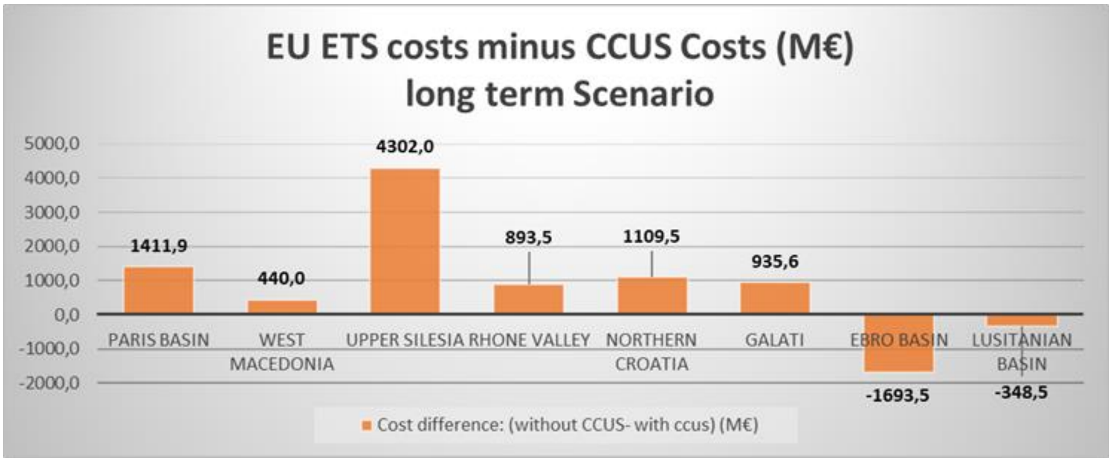


Figure 11. Financial gap costs between EU ETS and CCUS costs

4. Main findings of the eight CCUS techno-economic evaluation

Each CCUS deployment scenario is specific to the region analyzed and the choices made in the CCUS chain. The deployment and techno-economic analysis of the eight CCUS chains in Southern and Eastern Europe have yielded numerous lessons:

- The existing physical characteristics of each region, i.e., the number and type of high CO_2 emitting industries, existing transport networks, as well as the estimated storage capacities or long-term CO_2 utilization in the region, greatly influence regional deployment of CCUS.
- In the eight regions, nearly 78% of the CO_2 captured is avoided i.e., after subtracting the CO_2 used in the production of fast-moving consumer goods is released into the atmosphere. The efficiency of the scenario is of great importance and can be approached by the tons of CO_2 avoided per ton of CO_2 captured. Ebro Basin is the most efficient one with 0.95 t CO_2 avoided per t CO_2 captured.
- Each scenario has its own cost efficiency in terms of Euros per tons of avoided CO_2 which is based on the different costs and different avoidance potentials of the elements of the CCUS chain.
- The amount of CO_2 avoided (357 Mt) in the eight regions is greater than the amount of CO_2 stored (343 Mt) due to the long-term use of CO_2 in mineralization (Western Macedonia and Ebro Basin). This long-term use of CO_2 is of great environmental importance since it reduces the costs of CO_2 storage and increases the revenues of the CCUS chain and thus it should be promoted.
- In average, OPEX costs contribute 63% to the total CCUS costs and are mainly linked to energy consumption related. Reduction of these expenses should be a top priority to reduce the cost of the entire CCUS chain and the CO_2 emissions associated.
- Capture costs, tend to be higher for most of the industries other than power plants. This has a significant impact on the costs of the entire CCUS chain (capture costs generally represent the larger portion of total costs – 32% in average). More research and developed are thus necessary to reduce the capture costs for CO_2 intensive industries other than power plants and limit the costs of the CCUS chain.
- Guarantee of origin systems are necessary to implement for bioCO_2 capture. It is essential to trace bioCO_2 use, to certify whether it is a negative emission or not.
- The pooling of investment costs, particularly infrastructure costs, makes it possible to reduce the costs of the CCUS chain.
- Planning for the transportation and storage infrastructure needed to deploy CCUS over the long term is necessary.

5. Discussion

Economic study of the scenarios would benefit from a sensitivity analysis of the various investments and operational parameters of the CCUS modules such as the efficiency of the various CO_2 capture technologies considered, as well as the level of the storage resources (Tier 1 and Tier 2). As such, based on literature costs, an in depth and more detailed economic analyses should be conducted to reduce the economics uncertainties of the evaluation. It should be noted that the costs which are calculated are the costs associated with a technological deployment on a region for 25 years. This explains in part the relatively low cost expressed in euros per ton of avoided CO_2.

With respect to revenue gained from CO_2 sales, these values are likely to be overly optimistic because the CO_2 sales price is assumed to be equal to the study's EU ETS market price scenario (Table 1). This will probably depend on the speed of development of the CO_2 utilization market, but in the short term we can reasonably assume that the volume of CO_2 captured will be much higher than the volume of CO_2 needed for utilization and therefore the CO_2 selling price will probably be lower than the price on the EU ETS. Moreover, it should be underlined that the study did not consider the investment and operation costs of the different CO_2 utilization processes, which reduce the net revenues.

All estimated regional CO_2 deployment scenarios were considered within a region or country. However, for some scenarios (e.g., France), storage capacity is a limiting element for CCUS deployment. Opening the borders to CO_2 transport (at least in Europe) would allow for greater deployment of CCUS by allowing captured CO_2 to be transported to CO_2 storage areas.

6. Conclusion

In conclusion, there is not ONE CCUS scenario but AS many scenarios as there are regions. Depending on the industries investing in CO_2 capture technology, the use made of the captured CO_2, the mode of transport adopted and the local storage capacities, all scenarios are specific to the region and to the national public policies in place.

Similarly, there is not only ONE cost of CCUS, but specific costs related to each of the deployed scenarios.

Over a period of 25 years, the investment costs are distributed per ton of CO_2 avoided. For this reason, the costs of the eight scenarios should be compared to each other rather than considering the costs presented here as generic costs of CCUS. And in fact, the interest of the work lies in the comparison of the eight regional CCUS scenarios and regional lessons learned from them.

Considering the financial gap between CCUS costs and EU ETS, three scenarios make CCUS more attractive in our modelling: (1) Upper Silesia, which scenario is based on captured CO_2 on power plants and on 10 Mt CO_2 used for mineralization (4 302 M€ of lower costs with CCUS compared to EU ETS costs), followed by (2) Paris Basin, which 1/3 of avoided emissions are negative emissions (1 411.9 M€ but this case must be considered as a theoretical and exploratory one as it includes the incinerators in the EU ETS which IS NOT the case nowadays in France), and then (3) Northern Croatia with 1 162.5 M€ of lower costs with CCUS compared to EU ETS costs. On the other side, Ebro and Lusitania basins present higher costs of CCUS compared to their estimated EU ETS compliance costs.

It should be noticed that these results are highly influenced by the EU ETS scenario price.

For the eight regions, the share of CO_2 avoided through CCUS in the national greenhouse gas reduction strategy in 2050 varies from 9% for Western Macedonia, the Rhône Valley, and the Paris Basin for the lowest, to 33% for the Ebro Basin region, 43% for the Upper Silesia region, and 66% for the Lusitanian Basin which is the highest.

Considering these results, and to best incentivize CCUS scenarios, it is important to consider the following parameters:

- the environmental impact of CCUS in terms of volumes of CO_2 avoided,
- the efficiency of CCUS through the total investment cost per ton of CO_2 avoided,
- the reuse of the captured CO_2 when it is reused in long-life products,
- the storage and reuse in long-life products of captured bioCO_2 to favor high quantity of negative CO_2 emissions.

In the eight regions studied, common outcomes related to the economic analysis can be highlighted. For sake of example, the industrial sector and the public authorities should unify their strategies and roadmaps, to develop private-public partnerships to jointly proceed to investments and reduce the CAPEX by optimizing the infrastructures, which is particularly true for developing a pipeline transport network. All these parameters should be encouraged, but they are highly dependent on the regional characteristics of fossil energy production and consumption.

Acknowledgements

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