Economic Evaluation of CCUS Scenarios in Eight Southern and Eastern European Regions

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Editor: Paula Coussy

Authors:

Portugal: P. Fortes, P. Mesquita, P. Pereira, J. Carneiro, R. Aguiar, P. Rocha

Spain: R. Martínez, P. Canteli

France Rhône Valley: C. Dumas; P. Coussy

France Paris Basin: I. Gravaud, F. M.L. Veloso

Croatia: D. Vulin, L. Jukić

Poland: P. Krawczyk, A. Śliwińska, K. Stańczyk, J. Świądrowski, T. Urych

Greece: P. Tyrologou, D. Karapanos, R. Karametou, G. Maraslidis

Romania : A. Dudu, A. Nermoen

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Project Coordinator	Fernanda de Mesquita Lobo Veloso		07/07/2022

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Executive summary

Each CCUS deployment scenario presented in this report was carried out by dedicated regional teams and was previously presented, explained, and discussed in eight regional stakeholder committees organized as part of the project.

All scenarios developed are based on a set of regional and national data that were collected and shaped as part of the STRATEGY CCUS project.

All scenarios were evaluated using the same economic evaluation tool developed in the STRATEGY CCUS project. All eight scenarios used the same general macroeconomic assumptions. Thus, thanks to this common economic evaluation tool, eight very different regional CCUS deployment scenarios can be compared with each other for the first time in Europe.

Indeed, each CCUS deployment scenario is specific to the region analysed and the choices made in the CCUS chain. It depends on the existing and projected CO_2 emissions, the possible use of CO_2, the level of knowledge of storage capacities, the distances and modes of transport chosen...etc. Thus, each regional economic assessment of CCUS deployment is specific to a given region.

The deployment and technical-economic analysis of the eight CCUS chains in Southern and Eastern Europe have yielded numerous lessons. Among them we can mention:

- ✓ As a matter of course, the existing physical characteristics of each of the eight regions, 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 deployments of CCUS.
- ✓ Across the eight regions, nearly 78% of the CO_2 captured is ultimately avoided once the CO_2 used in the production of fast-moving consumer goods is released to the atmosphere (Figure 10). This ratio should be seen with great attention in terms of efficiency when deploying CCUS.
- ✓ Among the eight scenarios, Ebro Basin is the most efficient one with 0.955 tons of CO_2 avoided per ton of CO_2 captured.
- ✓ Each scenario has its own efficiency in terms of Euros per tons of avoided CO_2 and this efficiency 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. It should be promoted.
- ✓ In average, OPEX costs contribute 63% of total CCUS costs. These expenses should be reduced in priority to reduce the cost of the CCUS chain.
- ✓ Capture costs, for industries other than power plants are high. This has a significant impact on the costs of the entire CCUS chain (capture costs generally represent a significant portion of total costs – 32% in average). Capture costs for CO_2 intensive industries other than power plants must be reduced in the future to limit the costs of the CCUS chain.
- ✓ When bioCO_2 is captured, it is essential to trace its use to certify whether it is a negative emission or not. Indeed, when captured bioCO_2 is stored in geological reservoirs or used in

long-lived products such as mineralization[1], it may be considered a negative CO_2 emission. On the other hand, when the captured bioCO_2 is used in short-lived products such as synthetic fuels, it may be considered as avoided. Additional LCA-based analyses are needed to qualify net bioCO_2 emissions (avoided or removed).

- ✓ The pooling of investment costs, particularly infrastructure costs, makes it possible to reduce the costs of the CCUS chain

Considering the financial gap between CCUS costs and European Union - Emissions Trading System (EU-ETS), three long-term scenarios among those evaluated make CCUS more attractive (Figure 0-1): (1) Upper Silesia, which scenario is based on captured CO_2 on power plants and on 10 Mt CO2 used for mineralization (4 302 M€ of lower costs with CCUS compared to EU ETS costs[2]), followed by (2) Paris Basin including 9.1 Mt of negative emissions (1411.9 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 1109.5 M€ of lower costs with CCUS compared to EU ETS costs.

On the other side, Ebro and Lusitanian basins present higher costs of CCUS compared to the estimated EU ETS compliance costs.

These results are however highly influenced by the EU-ETS scenario price.

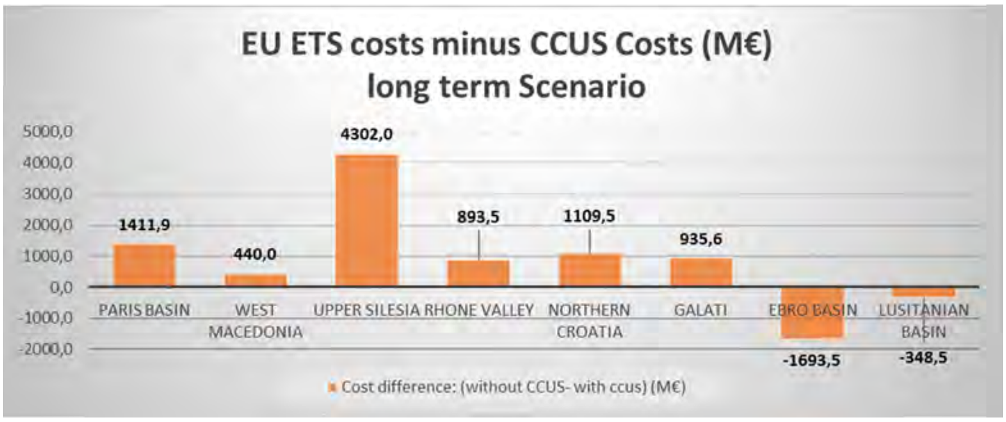

Figure 0-1 Financial gap between CCUS costs and EU ETS costs

To properly incentivise CCUS scenarios, it is important to consider a set of parameters, namely:

- ✓ the environmental impact of CCUS in terms of volumes of CO_2 avoided,
- ✓ the efficiency of CCUS through the total investment cost per tonne of CO_2 avoided,
- ✓ the reuse of the captured CO_2, in particular when it is reused in long-life products,

[1] This process of mineralization refers to a typical chemical reaction that takes place when certain types of minerals are exposed to CO_2, resulting in the CO_2 being transformed into rock (permanent storage of CO_2 as a solid, with no need for long term monitoring) at a pace which is driven by new technologies with improved cost performances that can force this process is much faster than what happens in a natural mineralization process. CO2 mineralization could occur under carbonation, concrete curing or novel cements.

[2] Based on the EUAs price scenario described in 2.2 General economic data

- ✓ the storage and reuse in long-life products of captured bioCO_2 to favour 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 optimising the infrastructures, which is particularly true for developing a pipeline transport network. Economic study of the scenarios would benefit from a sensitivity analysis of the various investment and operational parameters of the CCUS modules such as the efficiency of the various CO_2 capture technologies being considered, as well as the level of the storage resources (Tier 1 and Tier 2). As such, based on literature costs, an in deep and more detailed economic analyses should be conducted to reduce the economics uncertainties of the evaluation.

All these parameters should be encouraged, but they are highly dependent on the regional characteristics of fossil energy production and consumption.

Table des matières

Economic Evaluation of CCUS Scenarios in Eight Southern and Eastern European Regions

1 Introduction

The objective of this deliverable D5.3 is to present the economic evaluation of the eight regional Carbon Capture Utilization and Storage (CCUS) scenarios studied in: Ebro basin in Spain, Lusitanian basin in Portugal, Paris basin and Rhone valley in France, Northern Croatia, Galati region in Romania, Western Macedonia in Greece, and Upper Silesia in Poland.

Economic evaluation of each of the eight regional scenarios are presented in standalone parts. For these eight regions, a Main and Alternative scenario(s) are evaluated until 2050 with a mid-term evaluation point. Scenarios are defined by each regional team based on their own expertise and on their own regional characteristics and decarbonization strategies. All data used to construct the scenarios are public and collected as part of the STRATEGY CCUS project. No industry mentioned in this report has committed to any of the scenarios presented.

All the technical CCUS chain modules of these CCUS scenarios are presented in more detail in deliverable D5.2 “Description of CCUS business cases in Eight southern and eastern European regions” of STRATEGY CCUS project [1].

This deliverable D5.3 "Economic Evaluation of CCUS Scenarios in Eight Southern and Eastern European Regions" starts with the methodological approach used in the economic evaluation of the scenarios (chapter 2), followed (in chapter 3) by the analysis and comparison of the main findings of the regional scenarios, providing an overview and synthesis of the main scenario results and ends with the economic results obtained in the eight regions (chapters 4 to 10).

2 Methodological approach used in the economic evaluation of scenarios

2.1 Economic evaluation methodology

In each of the eight regions, two sets of scenarios are evaluated: a Main and an Alternative scenario(s). Both of them explore what the deployment of CCUS in a region might look like in 2050. The Alternative scenario(s) allow(s) for the exploration of some economic or technical parameters identified as uncertain, i.e., the total CO_2 storage availability or existing infrastructure of transport for example.

The overall time for scenarios deployment is the same for all eight regions and ranges from 2025 to 2050. For each of the eight regions short-term (from 2025 to 2035 or to 2040) and long-term (from 2025 to 2050) CCUS deployment scenarios are studied.

For each of the regional scenarios, the same set of Key Performance Indicators (KPIs) is provided, making it easy to compare the regional scenarios with each other (Figure 2-1 Architecture of the scenarios).

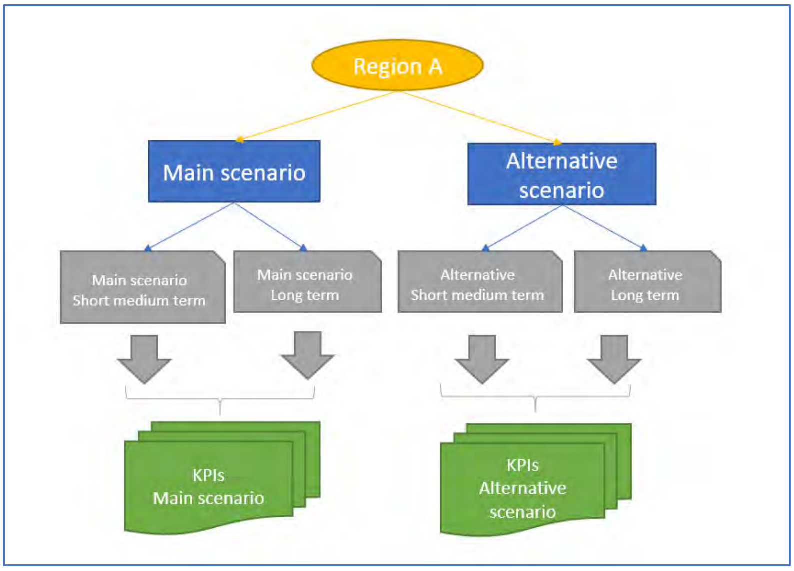

Figure 2-1 Architecture of the scenarios

The economic evaluation of the CCUS deployment scenarios takes into account the capital and operating costs throughout scenarios. The additional energy required for CCUS is accounted for and the associated CO_2 emissions, depending on the type of energy used (natural gas, fuel, electricity), are captured and accounted for.

The capital and operating costs for CO_2 transport are calculated according to the mode of transport used. For example, pipeline transport takes into account the topography and land use of the areas it crosses, and the pumping energy requirements 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 investments and associated operating costs are calculated according to the type of storage envisaged (oil reservoir 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 considered in the investments.

The main objective of the economic evaluation is to compare (1) the total costs that would result from investing in CCUS on a regional scale to (2) the estimated the EU-ETS compliance costs (in the absence of CCUS) in the same region and time scale.

In the economic analysis, the CO_2 used as feedstock to produce e-fuels or chemicals or in mineralization is sold at the EU ETS scenario price[3] and thus generates revenue on a regional scale. No further costs or revenues regarding CO_2 utilization (e.g., investment, product sales) are considered.

Furthermore, the economic evaluation differentiates bioCO_2 emissions from fossil CO_2 emissions. This leads in case of permanent storage or long-term use (i.e., mineralization) to negative CO_2 emissions.

The main KPIs evaluated for each regional scenario are as follow:

- the volume of CO_2 avoided, used, removed, and stored
- the total costs associated to the regional CCUS investments (€/tCO_2 avoided),
- the different costs of capture, transport, and storage (in €/tCO_2 avoided) per scenario,
- the revenues provided in the scenario from CO_2 sales to a specific use i.e., e-fuels, mineralization, or chemical products,
- the average yearly energy needs by scenario to implement CCUS in the region
- the CO_2 breakeven price for each of the regional CCUS scenarios allowing an equivalent choice between investing in CCUS or paying the costs of the EU ETS,
- the share of CO_2 emission reductions from regional CCUS scenarios in the national goal of zero emissions in 2050.

2.2 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 uses of the CO_2 if any in the scenario, and the mobilization of different storage sites depending on the volume of CO_2 captured and transported. The economic evaluation is realized for the entire time horizon from 2025 to 2050 for the long-term scenarios.

The investment and operating costs used in the economic evaluation are taken from the literature and are scaled for the different industries concerned. The investment costs are annualized all along the scenario's trajectories.

To have a homogeneous comparison between regions, some common economic values used in the economic assessment are fixed for all the regions (Table 2-1). The main values are the price reference year of the investments, the discount rate, the inflation rate, the learning cost factor, and the European Union Allowances (EUAs) price scenario on the EU-ETS.

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, the price of electricity, or the business tax level.

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[3] simplified assumption of the model

Table 2-1 Common economic data and regional sites specific data

Common economic data	Value	unit
Price reference year	2021	year
Discount rate	5	%
Inflation rate	2,5	%/year
Learning cost factor for capture	-1	% /year
EUAs on EU-ETS price (yearly average): MEDIUM scenario In 2021 In 2050	 70 212	 €/t CO_2 €/tCO_2

3 Analysis and comparison of the eight CCUS scenarios

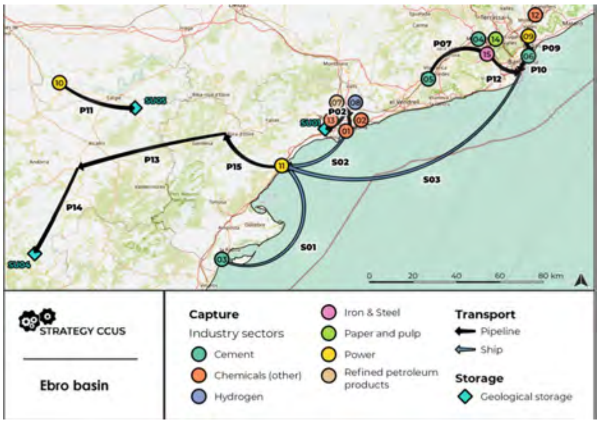
The following analysis of the eight regional CCUS scenarios[4] intends to synthetize the CCUS regional deployments and illustrate key findings and lessons learned.

As a matter of course, the **existing physical characteristics of each of the eight regions**, i.e., the number and type of high CO_2 emitting industries present on the territory, a possible existing pipeline or rail transportation network that could be used for CO_2 transport, as well as the estimated storage capacities in the region, **greatly influence regional deployments of CCUS**.

The eight regional scenarios presented in this report were considered in conjunction with national strategies to reduce CO_2 emissions by 2050. In general, they illustrate only one of several options for a potential national effort to reduce the emissions from CO_2-intensive industries.

Before summarizing the technical and economic results of the scenarios, Figure 3-1 presents a graphical overview and the main results of the eight CCUS scenarios.

3.1 Overview of the eight regional CCUS scenarios



EBRO Basin

CO_2 capture: 69.4 Mt including 1 Mt of $BioCO_2$

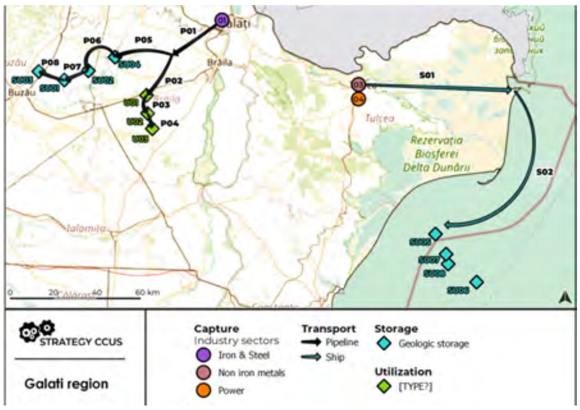
CO_2 used: 3.9 Mt

CO_2 stored: 65.5 Mt

CO_2 avoided: 66.3 Mt

CCUS cost: 92.8 €/tCO2avoided (discounted)

Revenues: 6.9 €/tCO2 avoided



Galati region

CO_2 capture: 45.2 Mt

CO_2 used: 5.8 Mt

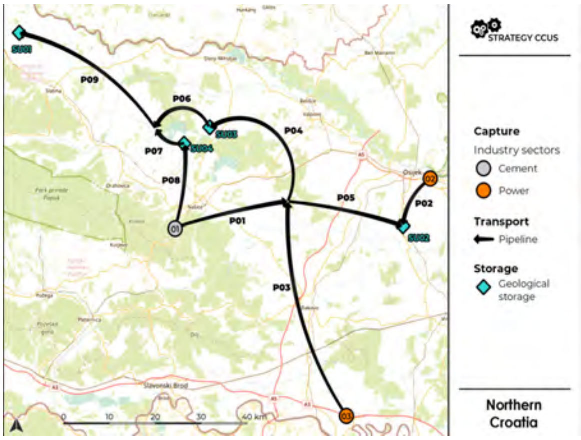
CO_2 stored: 37.4 Mt

CO_2 avoided: 39.2 Mt

CCUS cost: 42€/tCO2avoided (discounted)

Revenues: 15.4 €/tCO2 avoided

[4] For each region, only one long-term scenario is presented here, the Main one or the Alternative, depending on the teams' preference.



Northern Croatia

CO₂ capture: 29.8 Mt

CO₂ used: 1.1 Mt

CO₂ stored: 27.1 Mt

CO₂ avoided: 28.5 Mt

CCUS cost: 27€/tCO2avoided (discounted)

Revenues: 2.8 €/tCO2 avoided

Lusitanian basin

CO₂ capture: 93 Mt including 21.9 Mt of BioCO₂

CO₂ used: 32.5 Mt

CO₂ stored: 60.5 Mt

CO₂ avoided: 60.2 Mt

CCUS cost: 72€/tCO2avoided (discounted)

Revenues: 64.4 €/tCO2 avoided

Rhone Valley

CO₂ capture: 50.5 Mt including 2.2 Mt of BioCO₂

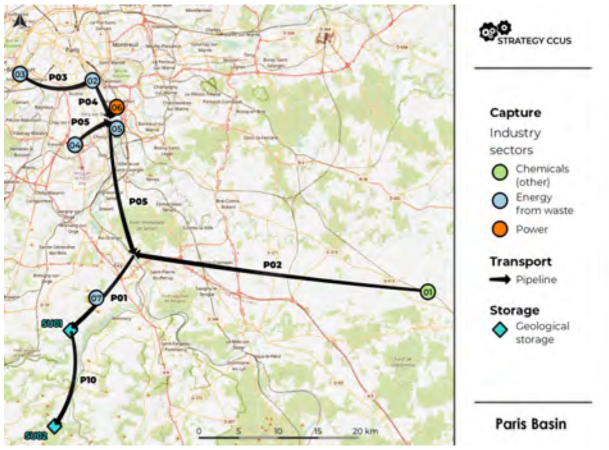
CO₂ used: 21.1 Mt

CO₂ stored: 29.4 Mt

CO₂ avoided: 29.3 Mt

CCUS cost: 41.3€/tCO2avoided (discounted)

Revenues: 73 €/tCO2 avoided



Paris basin

CO₂ capture: 29.8 Mt including 9.1 Mt of BioCO₂

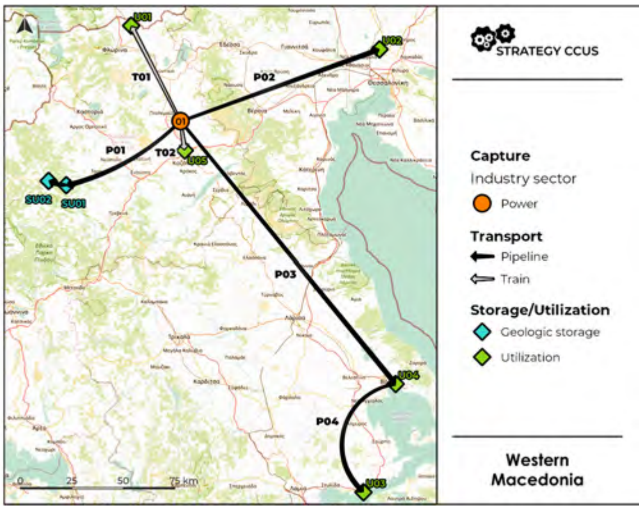
CO₂ used: 0 Mt

CO₂ stored: 29.8 Mt

CO₂ avoided: 29.7 Mt

CCUS cost: 39.4€/tCO2avoided (discounted)

Revenues: 0 €/tCO2 avoided



Upper Silesia

CO_2 capture: 100,5 Mt

CO_2 used: 13,2 Mt

CO_2 stored: 85,8 Mt

CO_2 avoided: 86,7 Mt

CCUS cost: 17,0 €/tCO2avoided (discounted)

Revenues: 15.3 €/tCO2 avoided

Western Macedonia

CO_2 capture: 38.9 Mt

CO_2 used: 31.7 Mt = 81.5%CO2 captured

CO_2 stored: 7.2 Mt

CO_2 avoided: 17.2 Mt

CCUS cost: 35.8€/tCO2avoided (discounted)

Revenues: 165.5 €/tCO2 avoided

Figure 3-1: Graphical and numerical summary of the eight CCUS scenarios

3.2 Synthesis of the eight long-term CCUS regional scenarios

3.2.1 Screenshot of the eight-regional long-term CCUS scenarios: volumes and costs

In the eight regions studied, long-term CCUS scenarios **capture 457 MtCO_2** in industries up to 2050. For comparison, in 2019, French CO_2 emissions represented 454.8 MtCO_2.

These same eight regions **use 23.8% (109 MtCO_2) of the CO_2 captured** as feedstock in the production of fuels, chemicals or in mineralization process.

Considering 1% of CO_2 losses all along transport and storage steps, nearly **343 MtCO_2 are thus stored**.

Once CO_2 used in the production of fast-moving consumer goods (such as fuels or chemicals) is released into the atmosphere, a net amount of **357 million tons of CO2 is ultimately avoided** through CCUS. Thus, across the eight regions, nearly **78% of the CO_2 captured is ultimately avoided** once the CO_2 used in the production of fast-moving consumer goods is released to the atmosphere. (Figure 3-2).

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).

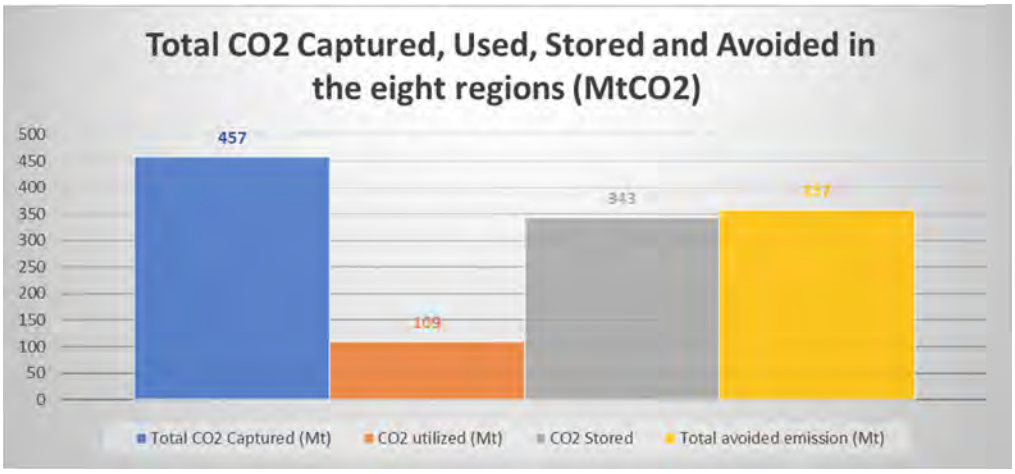


Figure 3-2: Total CO_2 Capture, Used, Stored and Avoided in the total of the eight regions

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€, (Figure 3-3).

In average and considering costs up to 2050, OPEX costs account for 63% of total CCUS costs, except for Paris Basin and Ebro Basin where OPEX account for 77% and 71% of the total CCUS costs respectively.

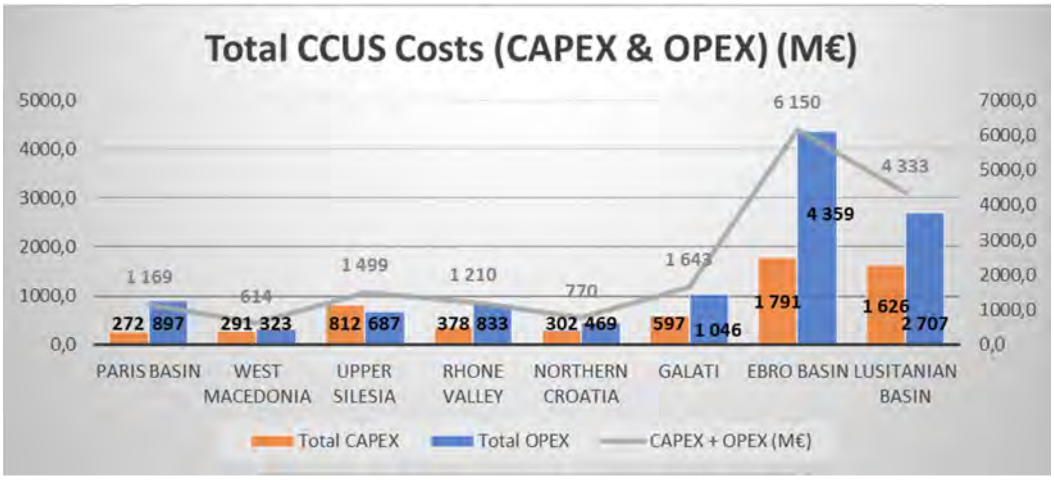


Figure 3-3: Total CCUS costs in the eight regions

3.2.2 Total amount of CO_2 avoided versus total CCUS costs (€/tCO_2 avoided) in the eight regions

An interesting point to note is the investment required per scenario and the associated cost per ton of CO_2 avoided – calculated over the (25 years) scenario period.

In terms **of volume of CO_2 avoided** (seen in Figure 3-11) the three first regions are: (1) Upper Silesia with 86.7 MtCO_2 avoided during the scenario, followed by (2) Ebro Basin with 66.3 MtCO_2 avoided and (3) Lusitanian Basin with 60.2 MtCO_2 avoided. In **terms of profitability of the CCUS investment** (€/tCO_2 avoided) the three first regions are: (1) Upper Silesia (with 17 €/tCO_2 avoided), (2) Northern Croatia (25.2 €/tCO_2 avoided) and (3) West Macedonia (35.8 €/tCO_2 avoided) (Figure 3-11).

Each scenario has its own efficiency in terms of avoided CO_2 and this efficiency is based on the different costs and different avoidance potentials of the elements of the CCUS chain.

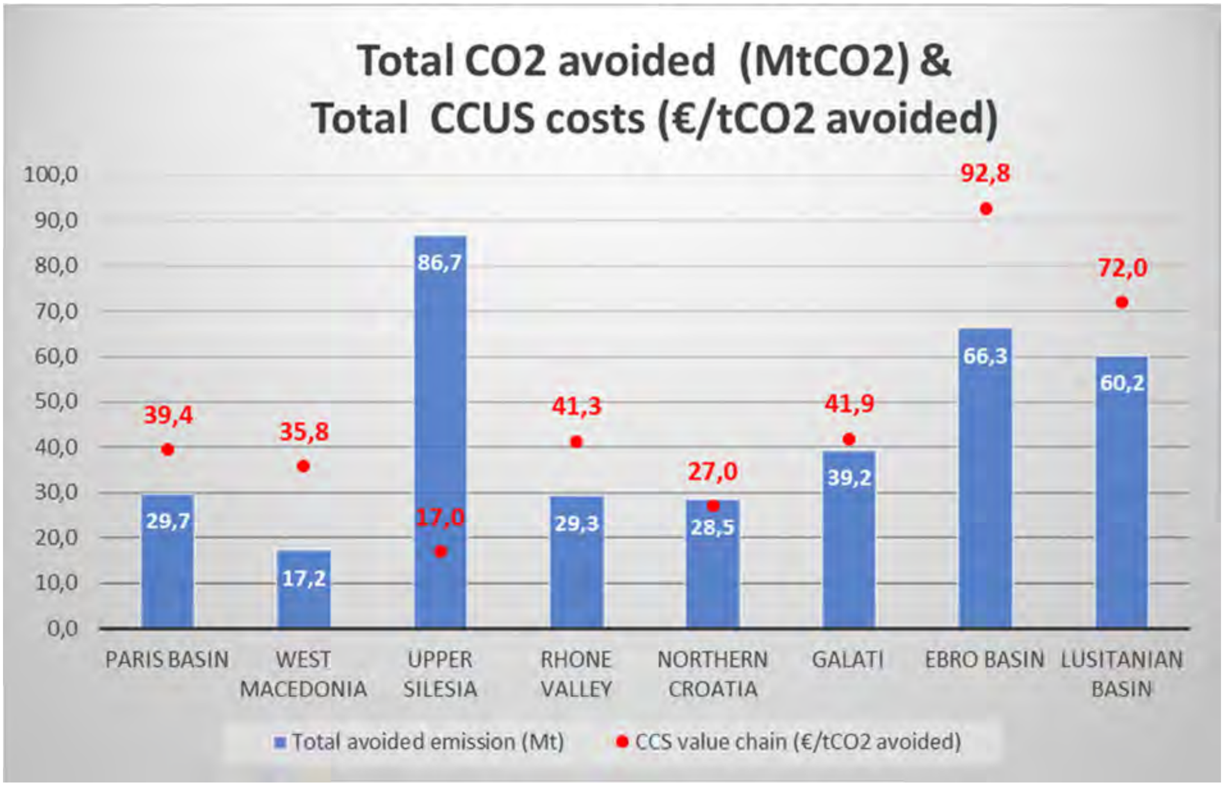


Figure 3-4: Total CO_2 avoided versus total CCUS costs (€/tCO_2 avoided) in the eight regions

3.2.3 CO_2 captured, avoided, used, and removed in the eight regions

Among the 457 MtCO_2 captured, the three regions with the most important volumes **of CO_2 captured** are: (1) Upper Silesia with 100 MtCO_2 captured until 2050 (21.9% of total CO_2 captured), following by (2) Lusitanian Basin with 93 MtCO_2 (20.3%) and Ebro Basin with 69.4 MtCO2 (13%).

Among the 457 MtCO_2 captured, **109 MtCO_2 are used in the scenarios**. The three most important regions in terms of CO_2 used are: (1) Lusitanian Basin with 32.5 MtCO_2 used (in methanation), following by (2) West Macedonia with 31.7 MtCO_2 used (in mineralization and e-fuels) and (3) Rhone Valley with 21.1 MtCO_2 used.

Among **the 357 MtCO_2 avoided**, the three regions with the most important volumes of CO_2 avoided are (1) Upper Silesia (86.7 MtCO_2 avoided – equivalent to 86.3% of CO_2 captured) followed by (2) Ebro Basin (66.3MtCO_2 avoided – equivalent to 95.5% of CO_2 captured) and Lusitanian Basin (60.2 MtCO_2 avoided – equivalent to 65.7% of CO_2 captured), (Figure 3-4)

Among the eight scenarios, Ebro Basin with 0.955 ton of CO_2 avoided per ton of CO_2 captured, Northern Croatia and Paris basin are the most efficient scenarios (Figure 3-4**).**

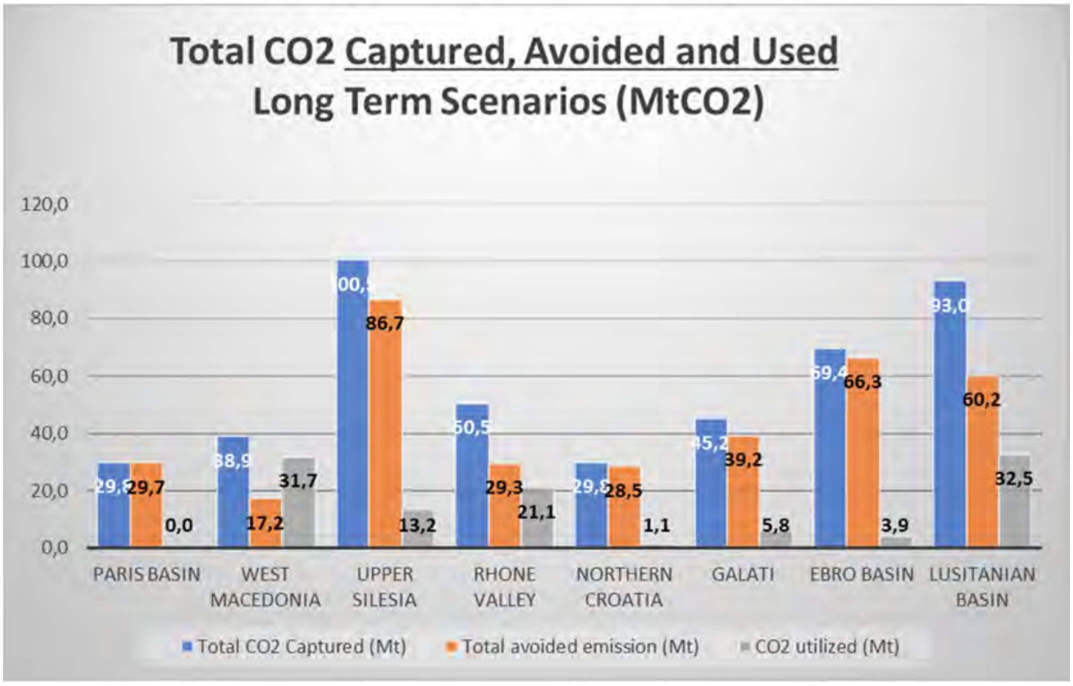


Figure 3-5: Total CO_2 capture, avoided and used in the eight regions

3.2.4 Costs of CO_2 captured in the eight regions

All costs are expressed in Euros per ton of CO_2 avoided and are based (for the most important assumptions) on the total lifetime of the scenarios, considering the learning curve (1 % per year), the total amount of CO_2 captured for 25 years, a discount rate of 5 % and the CAPEX.

Among the eight regions, capture costs vary widely from 8€/tCO_2 avoided in Upper Silesia (mainly due to the high amount of CO_2 avoided in the scenario - 86.7 MtCO_2 avoided – from power plants) to 64.5 €/tCO_2 avoided in Lusitanian Basin (due to higher capture costs on cement, lime, glass and pulp and paper industries).

Capture costs for industries other than power plants are higher, which has a significant impact on the costs of the entire CCUS chain (capture costs generally represent a significant portion of total costs).

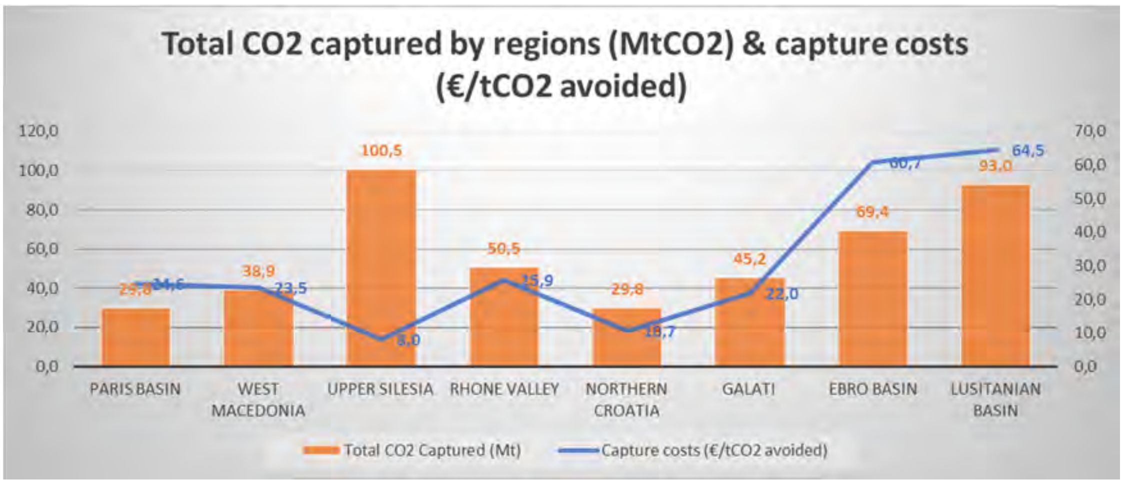


Figure 3-6: Total CO_2 captured by region & capture costs

3.2.5 BioCO_2 captured and CO_2 usages in mineralization

Among the 109 MtCO_2 used, 51% (56 MtCO_2) are used in mineralization usage or are bioCO_2 captured:

(1) Lusitanian Basin: 32.3 Mt BioCO_2 captured and used in methanation production which can't be accounted for negative emissions, (2) West Macedonia: 10 MtCO_2 non biogenic removed in mineralization not accounted as negative emissions, (3) Paris Basin: 9.1 MtCO_2 of bioCO_2 captured and stored which generates negative emissions, (4) Rhone Valley: 2.2 MtBioCO_2 captured and stored which generates negative emissions too and (5) Ebro Basin: 1.1 MtCO_2 used in mineralization which generates negative emissions only if it is BioCO_2 (Figure 3-7).

When bioCO_2 is captured, it is essential to trace the use of this bioCO_2 to certify whether it is a negative emission or not. Indeed, 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. Additional LCA-based analyses are needed to assess the net emissions avoided or removed.

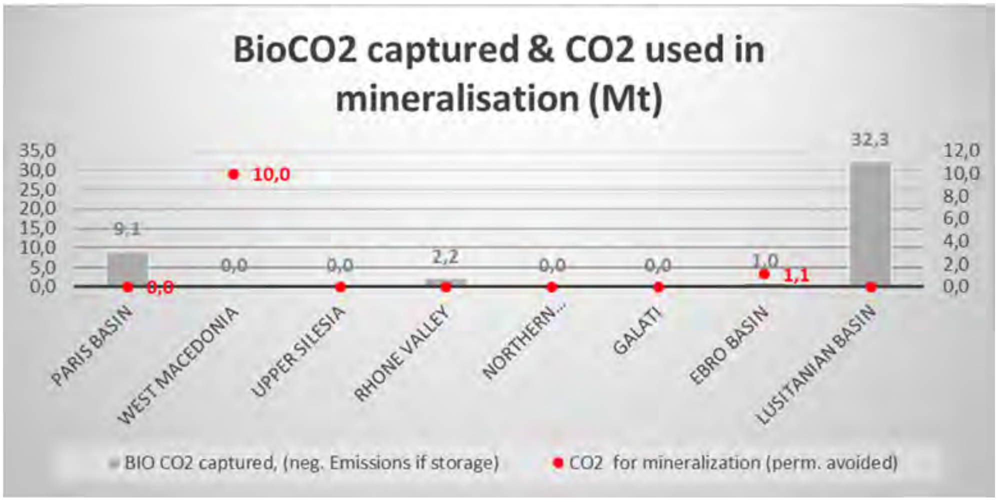


Figure 3-7: Total BioCO_2 captured, and CO_2 used in mineralization in the eight regions

3.2.6 Total CO_2 transported and transport costs by regions

A total **amount of 431 MtCO_2** are fed into different transport modes i.e., pipelines, trains, trucks, or ships.

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 due to the complex and long transport network based upon ships, pipeline, and trucks.

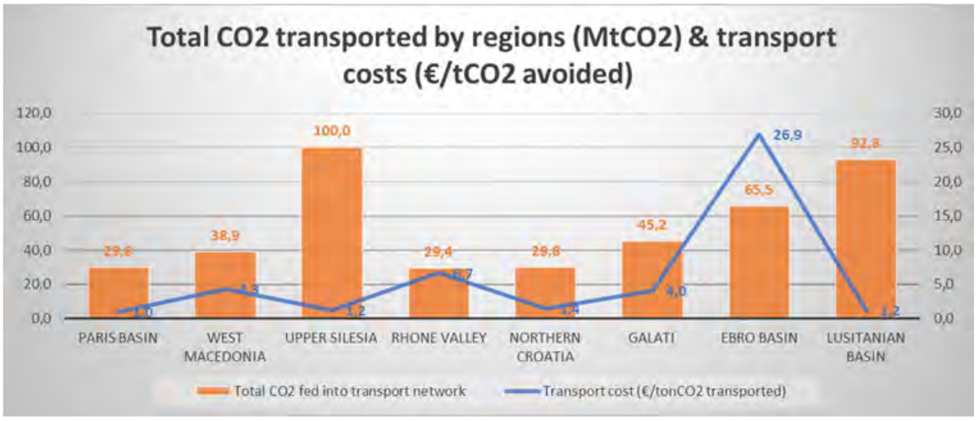


Figure 3-8: Total CO_2 transported by regions & transport costs

3.2.7 Total CO_2 stored and storage costs by regions

Among the 345 $MtCO_2$ stored in the eight regions, the three regions with the most important volumes of CO_2 stored are: (1) Upper Silesia (85.8 $MtCO_2$), (2) Ebro Basin (65.5 $MtCO_2$) and (3) Lusitanian Basin (60.5 $MtCO_2$).

The storage costs vary from 2.6 €/tCO_2 avoided in West Macedonia to 15.3 €/tCO_2 avoided in Galati region. The Galati region and northern Croatia have high storage costs due to enhanced oil recovery (EOR) operations before CO_2 storage later in the scenario.

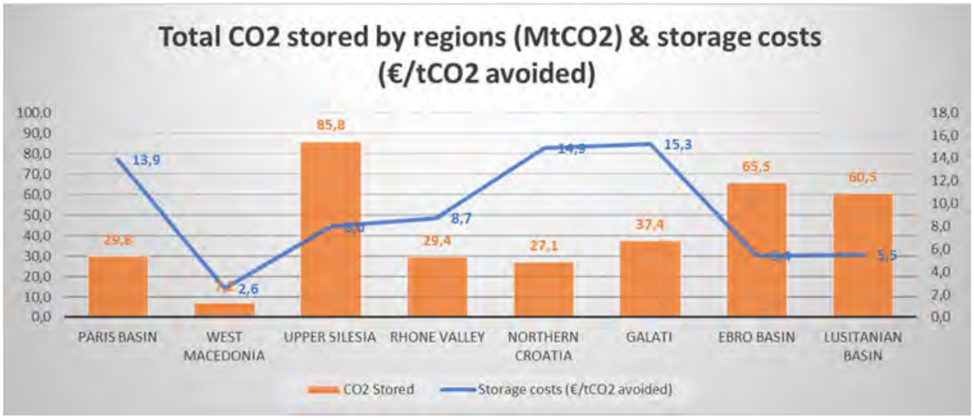


Figure 3-9: Total CO_2 stored by regions & storage costs

3.2.8 CCUS costs per tons of CO_2 avoided in the eight regions

A key parameter of interest for comparing the eight scenarios is the total cost per ton of CO_2 avoided. This ratio illustrates the costs per ton of CO_2 avoided for the entire duration of the scenario.

For the eight regions **the CCUS value chain ranges from 17€/tCO_2 avoided in Upper Silesia to 92.8 €/tCO_2 avoided in Ebro Basin for the long-term 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 tons 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) (Figure 3-10).

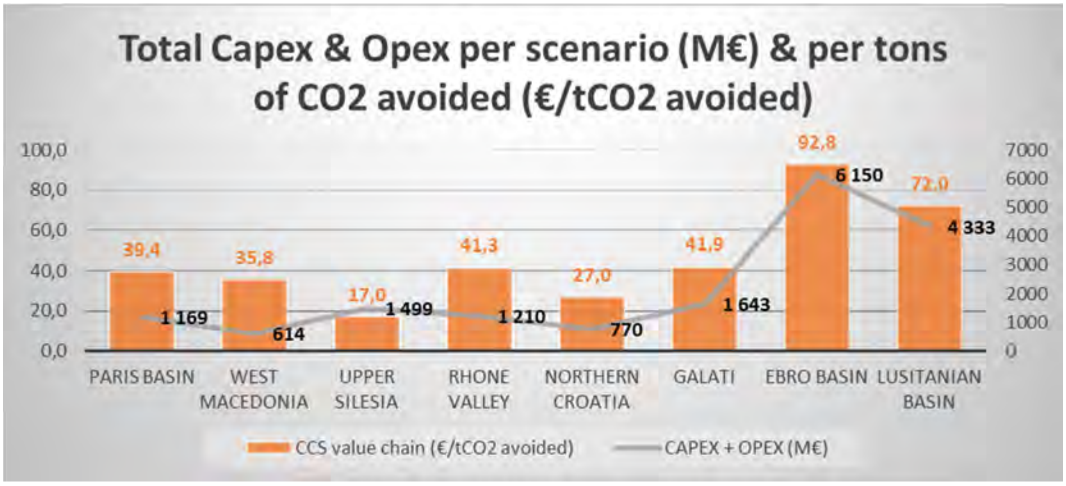


Figure 3-10: Total Capex/Opex per ton of CO_2 avoided (€/tCO_2 avoided) and per scenario (M€ discounted)

3.2.9 Total revenues generated by CO2 utilization

Related to **the 109 MtCO_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) Rhone Valley (2 146 M€) generate the biggest values (Figure 3-11)

These values are probably too optimistic because the CO_2 sale price is considered equivalent to the EU ETS market price scenario in the study. 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 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. To what extent? It is difficult to say now. 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.

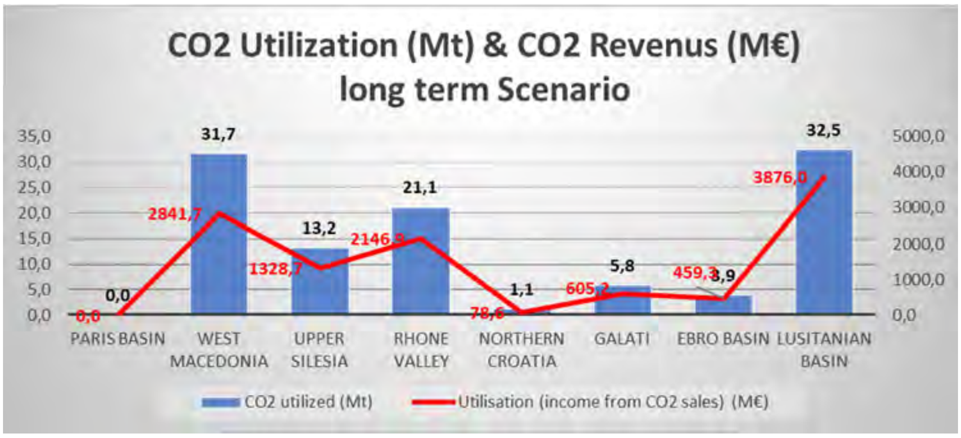


Figure 3-11: Total CO_2 used, and total revenues associated

3.2.10 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 what is anticipated in the future (Figure 3-12).

One way to do this is to compare the total cost of CCUS to the costs of compliance with the EU ETS and see the difference between the two (Figure 3-13).

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€ including a very strong hypothesis of the inclusion of the incinerators in the EU ETS which IS NOT the case nowadays in France), and then Northern Croatia with 1109.5 M€ of financial gap.

In two regions, which are Ebro Basin and Lusitanian Basin, with the economic hypothesis used in the analysis, it is financially more attractive to pay the EU ETS compliance costs than to invest in the CCUS. But in environmental point of view the Ebro Basin and Lusitanian Basin allow to avoid respectively 66.3 and 60.2 $MtCO_2$ avoided. For these two regions, the Ebro and Lusitanian basins, **public and private financial support of approximately 1,700 million euros for the Ebro basin and 350 million euros for the Lusitanian basin is needed** to make up the financial shortfall and enable the implementation of the CCUS.

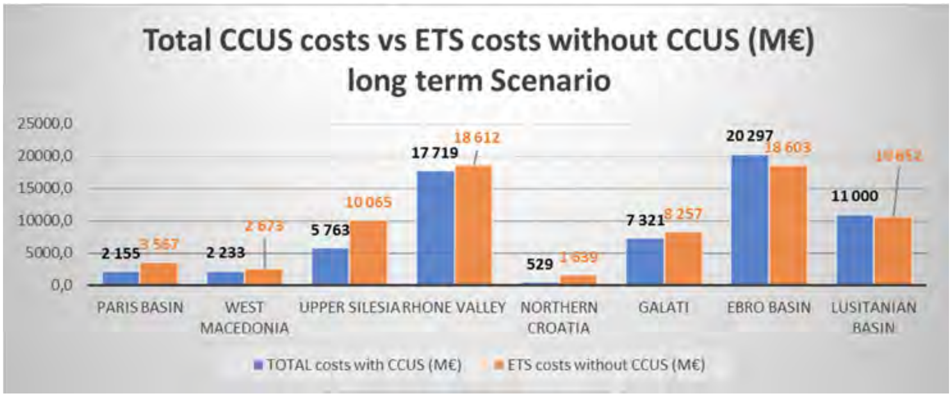


Figure 3-12: Total CCUS costs versus EU ETS compliance costs

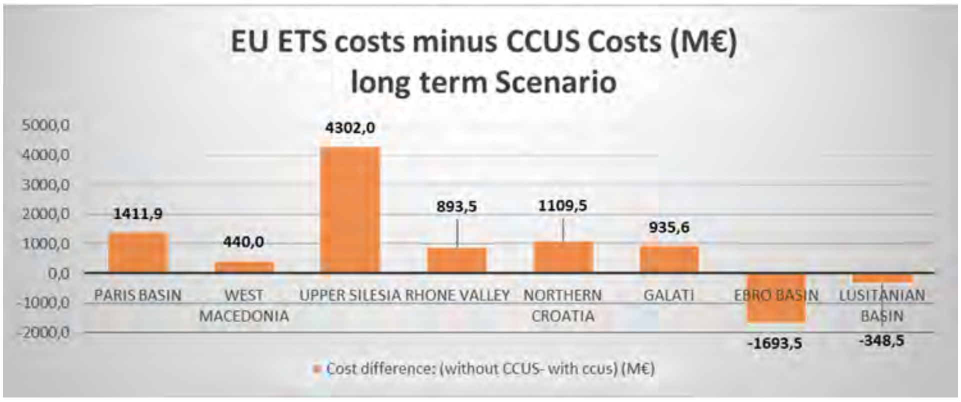


Figure 3-13: Financial gap costs between EU ETS and CCUS costs

3.2.11 Main findings of the eight CCUS techno-economic evaluation

The deployment and techno-economic analysis of the eight CCUS chains in Southern and Eastern Europe have yielded numerous lessons. Among them we can mention:

- ✓ As a matter of course, the existing physical characteristics of each of the eight regions, 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 deployments of CCUS.
- ✓ Across the eight regions, nearly 78% of the CO_2 captured is ultimately avoided including the CO_2 used in the production of fast-moving consumer goods, which is released to the atmosphere (Figure 10 2). This ratio should be seen with great attention in terms of efficiency when deploying CCUS.
- ✓ Among the eight scenarios, Ebro Basin is the most efficient scenario with 0.955 tons of CO_2 avoided per ton of CO_2 captured.
- ✓ Each scenario has its own efficiency in terms of Euros per tons of avoided CO_2 and this efficiency 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 CO2 storage and increases the revenues of the CCUS chain. It should be promoted.
- ✓ In average, OPEX costs account for 63% of total CCUS costs. These expenses should be reduced as a priority to reduce the cost of the CCUS chain.
- ✓ Capture costs, for industries other than power plants are high. This has a significant impact on the costs of the entire CCUS chain (capture costs generally represent a significant portion of total costs – 32% in average). Capture costs for CO_2 intensive industries other than power plants must be reduced in the future to limit the costs of the CCUS chain.
- ✓ When bioCO_2 is captured, it is essential to trace its use to certify whether it is a negative emission or not. Indeed, when captured bioCO_2 is stored in geological reservoirs or used in long-lived products such as mineralization[5], it may be considered a negative CO_2 emission. On the other hand, when the captured bioCO_2 is used in short-lived products such as synthetic fuels, it may be considered as avoided. Additional LCA-based analyses are needed to qualify net bioCO_2 emissions (avoided or removed).
- ✓ The pooling of investment costs, particularly infrastructure costs, makes it possible to reduce the costs of the CCUS chain

[5] This process of mineralization refers to a typical chemical reaction that takes place when certain types of minerals are exposed to CO2, resulting in the CO2 being transformed into rock (permanent storage of CO2 as a solid, with no need for long term monitoring) at a pace which is driven by new technologies with improved cost performances that can force this process is much faster than what happens in a natural mineralization process. CO2 mineralization could occur under carbonation, concrete curing, or novel cements.

4 Spain: Economic Evaluation of the regional CCUS scenario in the Ebro basin

4.1 Spain: Main Short- and medium-term Scenario

4.1.1 Cluster(s) emissions before CCUS

In the Ebro Basin scenario, a total number of 15 emitting facilities have been included in the global analysis. The mid-term scenario has been focused as a pilot test in the chemical industries at the Tarragona hub. In this scenario (2027 – 2036), only two emitters are involved. Reported emissions of these facilities are up to 1.87 Mt/year. In the final year of this scenario, total reported emissions without CCUS would reach 18.7 Mt of CO_2.

4.1.2 Emitters considered for capture technology

The 2 facilities indicated are listed in the following table:

Table 4-1 Industries with capture. Ebro Basin

Industries with capture per hub		
	Dow chemical iberica (dow nord)	Repsol quimica
Sector	Chemicals (other)	Chemicals (other)
CO_2 reported (Mt)	1.03	0.84
CO_2 captured (from fossil fuel) – Mt CO_2 /yr	0.411	0.336
Year to start capture	2027	2027
Total CO_2 captured (from fossil fuel) – Mt CO_2 in 2036	4.11	3.36
Total costs (€/t CO_2 avoided)	145.01	156.78

4.1.3 Transport mode

This scenario is based in a very simple network, in which only two pipelines are constructed, the first one connecting the two emitting facilities, and a second pipeline that connects them to the storage site of Reus. As a summary, transport options are listed in the following table:

Table 4-2 Transport mode. Ebro basin

Transport mode		
Type: Pipeline*, Ship, Truck	P*	P*

From	E01	E02
To	E02	SU01
Start year	2027	2027
Total CO_2 transported (2036)	5	10
Total Capex/Opex (€/t CO_2 avoided)	0.20	0.38

4.1.4 CO_2 Utilization

In the Main Scenario, the utilization of CO_2 is only related to pure CO_2 devoted to other industrial uses, with a very limited impact in the outcomes of the evaluation, both in the amount of CO_2 used and in the expected revenue.

Table 4-3 CO_2 utilization. Ebro Basin

CO_2 utilization	From industry E01 and E02
To industry	Pure CO_2 for other industrial uses
Total CO_2 used (t) in 2036	60,000
Total revenues from CO_2 used (M€)	2.78

4.1.5 Storage considered in the clusters

Only one storage unit plays a role in this scenario. CO_2 from E01 and E02 facilities would be stored in SU01 (Reus saline aquifer). The numbers of the storage operations by 2036 are listed in the following table:

Table 4-4 Storage. Ebro Basin

Storage	
	Storage 1
Localisation	Reus
Start date of storage	2027
Total CO_2 stored (Mt) in 2036	7.41
Total Capex/Opex (€/t CO_2 avoided)	2.34
Total energy used (MWh)	7.27E06

4.1.6 KPIs of the Scenario

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-57
Total CAPEX per block	**-20**
Cost of Capture (€/tonCO2 avoided)	-18
Cost of Transport (€/tonCO2 avoided)	-0,2
Cost of Storage (€/tonCO2 avoided)	-1,4
OPEX per block	**-37**
Cost of Capture (€/tonCO2 avoided)	-30
Cost of Transport (€/tonCO2 avoided)	-1
Cost of Storage (€/tonCO2 avoided)	-7
Transport cost (€/tonCO2 transported)	-0,7
Utilisation (income from CO2 sales) (M€)	6,0
EUA/ETS credit savings in the region (M€)	487,0

Analysis of CO2 volumes (Mt)

Total CO2 Captured	7,5
CO2 utilized	0,1
CO2 for mineralization (perm. avoided)	0,0
Stored	7,4
Total emitted with CCS	41,1
Total avoided emission	7,4
BIO CO2 captured, neg. Emissions	0,0
Total CO2 fed into transport network	**7**
CCUS National Objectives	200
Share in national objectives	3,7 %

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Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	212
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	3 571,7
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	3 084,7
Cost of CCUS (M€)	417,3
TOTAL costs with CCUS (M€)	**3 502,0**
Cost difference, with minus without CCUS (M€)	**-70,0**
Average yearly energy need, TWh/year	**0,24**
Peak energy need, TWh/year	**0,73**
Breakeven CO2 price (€/tonCO2)	52

This scenario can only be considered as a **pilot exercise** for the deployment of a CCUS scenario. But some previous conclusions can be taken from the scenario:

- Ten years is a too short term for a CCUS network, even if only considering a small hub, as the investment in the beginning (CAPEX) is quite high and requires longer periods to be recovered. To avoid this distortion, CAPEX has been annualized for a longer period, making results more coherent. In this sense, the development of the scenario has been optimized taking in account best possible operation of the storage site (injection rate, pressure control…) in the long term, and not regarding the costs.
- The cost of CCUS networks is mainly related to the capture phase. CCUS deployment needs innovation and reduction of costs in this first stage to be more competitive. Capture costs estimated from bibliography might be better assessed by the chemical industry.

Taking all these into account, the breakeven price for CO_2 allowances in this scenario is situated in 52 €/ton, making the project profitable from 2033. If these numbers come to reality, the deployment of this scenario could be considered a "low hanging fruit" for CCUS technologies.

4.2 Spain: Main Long-term scenario 2050

4.2.1 Cluster(s) emissions before CCUS

In the Ebro Basin scenario, a total number of 15 emitting facilities have been included in the analysis. Reported emissions of these facilities are up to 9.73 Mt/year. As 2027 is the year that has been projected as the one to initiate capture in chemical plants, in the year 2050 (long term), total emissions without CCUS of the hub would reach 291 Mt.

4.2.2 Emitters considered for capture technology

The 15 facilities indicated are listed in the following table

Table 4-5 Industries with capture. Ebro Basin

Industries with capture per hub															
	Dow chemical iberica	Repsol quimica	Cemex españa operaciones	Cementos molins industrial	Cementos portland valderrivas	Lafarge cementos	Repsol petróleos. A.	Hyco	Central termica	Central de escatron	Central de ciclo combinado plana del vent	Stahl iberica	Industrias quimicas del oxido de etileno	Barcelona cartonboard	Compañia española de laminacion
Sector	Chemicals (other)	Chemicals (other)	Cement	Cement	Cement	Cement	Refined petroleum products	Hydrogen	Power	Power	Power	Chemicals (other)	Chemicals (other)	Paper and pulp	Iron & Steel
CO2 reported (Mt)	1.03	0.84	0.78	1.14	1.10	0.43	2.29	0.38	0.38	0.34	0.34	0.21	0.11	0.19	0.18
CO2 captured (from fossil fuel) – MtCO2/yr	0.411	0.336	0.389	0.569	0.548	0.216	1.145	0.190	0.189	0.171	0.169	0.063	0.041	0.051	0.046
CO2 captured (from Biomass) – MtCO2/yr	0	0	0	0	0	0	0	0	0	0	0	0.044	0.012	0.042	0

Year to start capture	2027	2027	2033	2035	2038	2040	2038	2038	2040	2035	2040	2040	2045	2040	2040
Total CO_2 captured (from fossil fuel) – $MtCO_2$ in 2050	9.86	8.08	7.01	9.10	7.12	2.38	14.89	2.47	2.08	2.73	1.86	0.693	0.246	0.561	0.51
Total CO_2 captured (from Biomass) – $MtCO_2$ in 2050	0	0	0	0	0	0	0	0	0	0	0	0.484	0.072	0.462	0
Total costs (€/tCO_2 avoided)	100.13	107.47	155.95	144.09	157.67	204.37	166.11	139.08	163.43	169.97	133.85	166.58	185.66	385.33	692.80

4.2.3 Transport mode

This scenario uses all transport modes available.

- Ships are used to transport CO_2 from the industries in the Barcelona area to the port of Alcanar.
- Trucks are mainly used for short distance onshore transport from smaller facilities to the industrial hub.
- Pipelines are used for onshore transport in long distance or large quantities.

As a summary, transport options are listed in the following table:

Table 4-6 Transport mode. Ebro basin

Transport mode																				
Type: Pipeline[1], Ship[2], Truck[3]	P[1]	P[1]	P[1]	S[2]	P[1]	P[1]	P[1]	T[3]	T[3]	P[1]	P[1]	T[3]	P[1]	P[1]	S[2]	P[1]	T[3]	P[1]	P[1]	P[1]
From	E01	E02	E03	H09	E08	E07	H12	E11	E15	E14	E05	E12	E06	E09	H13	E10	E13	E04	H15	H16
To	E02	SU01	H09	H14	E07	H12	H14	H14	E04	E04	E15	E06	E09	H13	H14	SU05	H12	H13	H16	SU04
Start year	2027	2027	2036	2036	2038	2038	2038	2036	2038	2040	2038	2040	2040	2040	2035	2042	2040	2035	2036	2036
Total CO_2 transported (2050)	12	24	7.5	7.5	6.5	52	65	120	0.65	1.1	10.4	1.1	5.5	11	48	4.5	0.55	120	120	10.4
Total Capex/Opex (€/t CO_2 avoided) M€	0.07	0.15	0.05	8.43	0.09	0.20	5.22	0.52	0.0	0.0	1.26	0.0	1.31	0.66	5.86	4.24	0.0	0.61	2.73	0.84
Total energy used (MWh/year)				1.6E08			1.4E09	1.1E09	1.1E04	9.1E03		9.1E03	3.6E06		1.0E09		9.1E03		1.4E08	4.8E08

4.2.4 CO_2 Utilization

In the long-term scenario, four different uses for CO_2 are expected. The use of pure CO_2 for other industrial purposes is expected to come from the chemical industries, while mineralization will be produced from CO_2 captured at cement plants. Refineries will supply CO_2 for methanol production and finally, synthetic fuels will be produced from other industries in the latter part of the scenario.

Table 4-7 CO_2 utilization. Ebro Basin

CO_2 utilization	From industry E01 and E02	From industry E04, E05 and E06	From industry E07	From industry E12, E13 and E15
To industry	Pure CO_2 for other industrial uses	Mineralization	Methanol	Fuels
Total CO_2 used (t) in 2050	538,500	1,137,500	16,500,000	600,000
Total revenues from CO_2 used (M€)	24.93	5.69	76.40	30

4.2.5 Storage considered in the clusters

Only three storage units play a role in this scenario. CO_2 from E01 and E02 facilities would be stored in SU01 (Reus saline aquifer). CO_2 from E10 would be stored in SU05 (Caspe saline aquifer). The rest of industrial facilities would be transporting and storing CO_2 captured in SU04 (Maestrazgo saline aquifer). Some numbers of the storage operations by 2040 are listed in the following table:

Table 4-8 Storage. Ebro Basin

Storage	Storage 1	Storage 2	Storage 3
Localisation	Reus	Maestrazgo 3	Caspe
Start date of storage	2027	2033	2035
Total CO_2 stored (Mt) in 2050	17.40	45.40	2.70
Total Capex/Opex (€/t CO_2 avoided)	2.54	6.04	39.57
Total energy used (MWh)	1.71E+07	2.33E+05	1.45E+04

4.2.6 KPIs of the Scenario

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-93
Total CAPEX per block	**-27**
Cost of Capture (€/tonCO2 avoided)	-22
Cost of Transport (€/tonCO2 avoided)	-4
Cost of Storage (€/tonCO2 avoided)	-1
OPEX per block	**-66**
Cost of Capture (€/tonCO2 avoided)	-39
Cost of Transport (€/tonCO2 avoided)	-22
Cost of Storage (€/tonCO2 avoided)	-4
Transport cost (€/tonCO2 transported)	-26,9
Utilisation (income from CO2 sales) (M€)	459,3
EUA/ETS credit savings in the region (M€)	4456,8

Analysis of CO2 volumes (Mt)

Total CO2 Captured	69,4
CO2 utilized	3,9
CO2 for mineralization (perm. avoided)	1,1
Stored	65,5
Total emitted with CCS	153,1
Total avoided emission	66,3
BIO CO2 captured, neg. Emissions	1,0
Total CO2 fed into transport network	**66**
CCUS National Objectives	200
Share in national objectives	33,2 %

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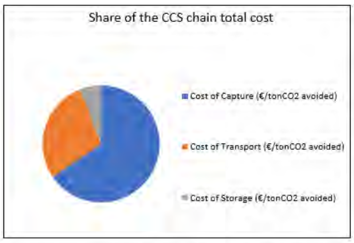
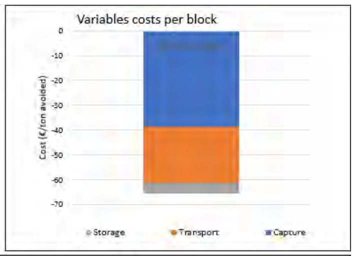
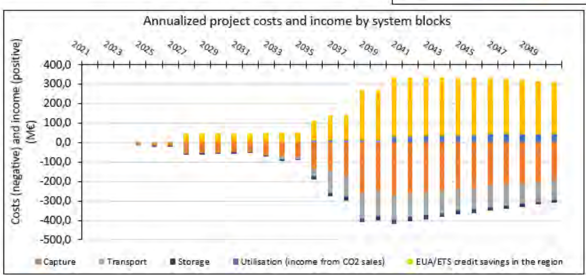
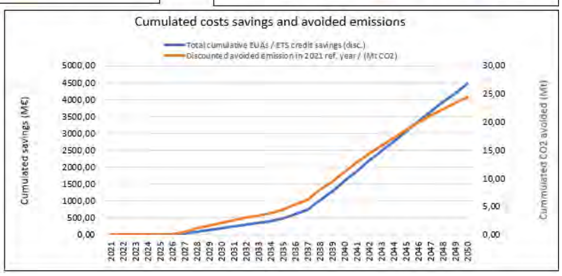
Analysis of ETS allowances

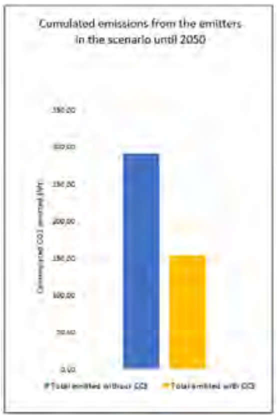
EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	212
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	18 603,5
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	14 146,7
Cost of CCUS (M€)	6 150,3
TOTAL costs with CCUS (M€)	**20 297,0**
Cost difference, with minus without CCUS (M€)	**1 694,0**
Average yearly energy need, TWh/year	**6,36**
Peak energy need, TWh/year	**13,60**
Breakeven CO2 price (€/tonCO2)	85

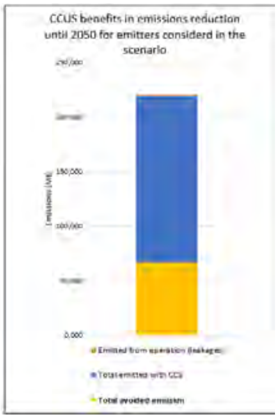












The Main Scenario has become extremely complex for the economic evaluation. Starting capture year is very variable in the different industrial hubs (based on national strategies and sectorial roadmaps). Those facilities included with capture starting years from 2040 have too short time to recover investments. Therefore, annualized calculation of the CAPEX is much more realistic. Single networks for single facilities are also non-economic options.

On the other hand, those facilities included in the short-term scenario show large reductions (25%) of their cost per ton CO_2 avoided when they get to the long term. Transport costs are much higher when including ships, which was expected as distances covered by vessels are not very long.

4.3 Spain: Alternative(s) scenario

4.3.1 Difference with the Main scenario

In the Alternative scenario, only those industries in which CCUS is part of the industrial strategy (sectorial roadmaps or companies' objectives) are considered for CCUS deployment. These industries, following industrial roadmaps, are supposed to start capturing in different stages, from 2033 to 2040. Only one storage unit is used but a complex transport network needs to be deployed, using **three different seaports and a long pipeline to reach the only storage unit** with enough capacity to store the total CO_2 captured. No biomass fired power plants are included in this scenario and therefore, no negative emissions are in place. This scenario is difficult to optimize but has been considered as more realistic than the previous one.

4.3.2 KPIs of the Alternative scenario

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-90
Total CAPEX per block	**-19**
Cost of Capture (€/tonCO2 avoided)	-13
Cost of Transport (€/tonCO2 avoided)	-5
Cost of Storage (€/tonCO2 avoided)	-1
OPEX per block	**-71**
Cost of Capture (€/tonCO2 avoided)	-41
Cost of Transport (€/tonCO2 avoided)	-26
Cost of Storage (€/tonCO2 avoided)	-3
Transport cost (€/tonCO2 transported)	-31,6
Utilisation (income from CO2 sales) (M€)	236,7
EUA/ETS credit savings in the region (M€)	2953,1

Analysis of CO2 volumes (Mt)

Total CO2 Captured	45,9
CO2 utilized	2,0
CO2 for mineralization (perm. avoided)	0,8
Stored	43,9
Total emitted with CCS	48,6
Total avoided emission	44,4
BIO CO2 captured, neg. Emissions	0,0
Total CO2 fed into transport network	**44**
CCUS National Objectives	200
Share in national objectives	22,2 %

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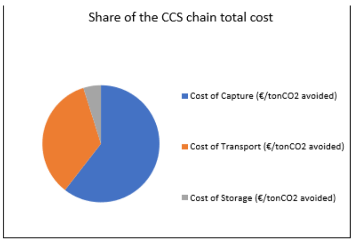
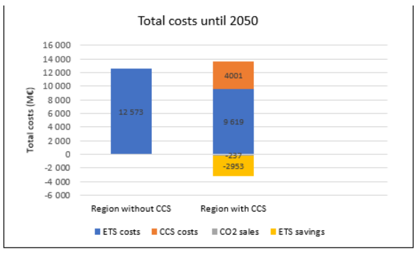
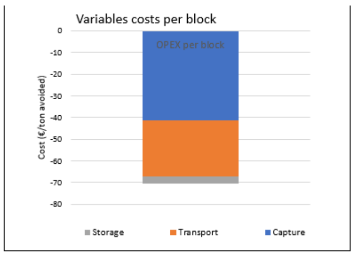
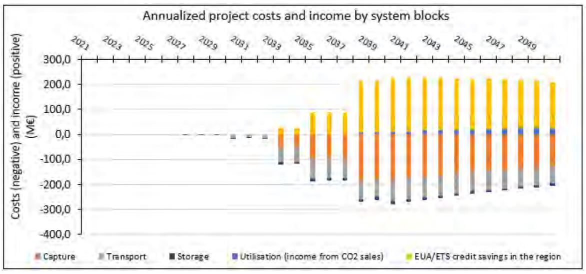
Analysis of ETS allowances

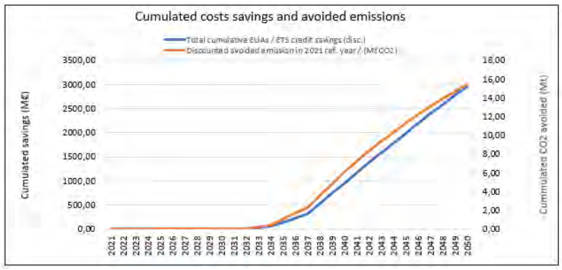
EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	212
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	12 572,5
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	9 619,5
Cost of CCUS (M€)	4 000,5
TOTAL costs with CCUS (M€)	**13 620,0**
Cost difference, with minus without CCUS (M€)	**1 047,0**
Average yearly energy need, TWh/year	**5,30**
Peak energy need, TWh/year	**11,33**
Breakeven CO2 price (€/tonCO2)	83

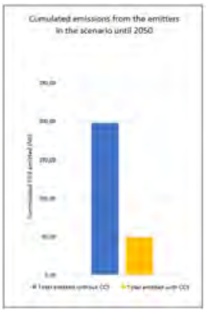


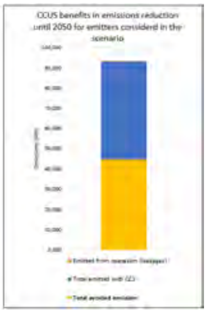












4.4 Conclusion of the economic assessment of Ebro basin scenarios

For a more effective deployment of these technologies, it should be suggested to the industrial sector and the Administrations to unify their strategies and roadmaps, to make common investments and reduce as much as possible the CAPEX and the periods when revenues are very low compared to the elevated costs.

Ships are a good option for transporting CO_2 avoiding mainland transport issues (land use, permits, etc.), but costs are too high if specific ships need to be built for the scenario development. Ship rental, if possible, could be an alternative option to reduce this cost. Anyway, the distances involved in sea transport for this scenario are not very long, reducing ship use advantage versus pipelines. In other scenarios with larger sea distances, ship transport economics would be more competitive.

R&D investment for capture technologies is extremely necessary for CCUS deployment, as the cost of capture is about 80% of the total costs, following this analysis. The reduction of this cost would enhance the operation and reduce the breakeven CO_2 price value. This analysis has been quite conservative regarding the amount of CO_2 that will be captured (40 – 50% of the last reported emission), as it is assumed that other additional measures to reduce the emissions will be taken, as the increase of energy efficiency or fuel switching, but it would be interesting to update the economic assessment with more optimistic numbers (i.e., 66%).

On the other hand, CO_2 utilization is included in an optimistic point of view, which may be realistic in an industrial hub with an important share of the chemical and oil and gas refining industry. The storage phase is very close to the numbers that will take place in the future, as all the operational costs are very well known through the oil and gas industry.

The Alternative scenario is more likely to happen than the Main scenario. Now, it is not very clear that gas fired power plants will still be operating by the 2040^{s}. Moreover, some isolated facilities that would need a specific transport and storage network will probably not participate in a global hub scenario. This industrial scenario needs to be refined, especially in the transport phase, establishing a common starting point for capture operations. From the technical point of view, it would be interesting that this starting point was set as soon as possible (2027?).

5 Portugal: economic evaluation of the Lusitanian basin

5.1 Lusitanian Basin: Main Scenario Short- and medium-term

5.1.1 Cluster(s)r emissions before CCUS

The total fossil CO_2 emissions from the major industrial sites in the Lusitanian Basin are around 12.66 Mt (2018 values identified in WP2 of the STRATEGY CCUS project), associated with cement, lime, glass, paper and pulp, ceramics, and power generation industries. These represented 42% of the national stationary CO_2 emissions in 2018 [1] and 97% of total emissions in the region.

After Portugal committed to the carbon neutrality goal up to 2050 (APA, 2019), several national industries and their respective associations have set ambitious decarbonisation strategies and targets, including the cement and the paper and pulp industries. The increase of energy efficiency, the shift to lower emissions fuels and renewables and the deployment of lower emissions processes have been thus set and implemented. In 2020, for example, the paper and pulp industry of Figueira da Foz (Navigator, 2020) has replaced its natural gas boiler with a biomass one, and the coal Pego power plant has closed its activity at the end of November 2021. Due to the industry and power decarbonisation plans, more changes are expected to occur in the region towards a reduction of CO_2 emissions in the short, medium, and long term as compared with 2018 values.

Thus, to consider the uncertainty of the Lusitanian Basin CO_2 emissions this report considers two main emissions (and consequently CCUS chain) scenarios, delimiting the upper and lower bounds of CCUS potential and costs[6]:

i. Business-as-usual (BAU): assumes that industries carbon intensity and fuel consumption profile identified in WP2 will not change in the future (except for the changes already verified such as in emitter E#15).

ii. Decarbonisation Pathway (DECARB): considers that industries will implement their decarbonisation plans, leading to a reduction of carbon intensity and a shift in fuel consumption. The main decarbonization strategies are linked to the overall national Cement [4] and the Navigator paper and pulp industries [4], which aim to be carbon neutral up to 2050 and 2035, respectively.

5.1.2 Emitters considered for capture technology

Capture technologies are not expected to be fully deployed before 2035 although two pilot units are planned by the cement and glass industries as shown in Table 5-1. These represent a small-scale, and short-term installations with low capture efficiency (<10%, i.e., less than 10% of the CO_2 mass in the industrial flue gas, including the CO_2 resulting from the additional energy required by the capture facility, is targeted by the capture process) which helps facilities learn and test technologies for large-scale projects in the future.

[6] All values presented in this report regarding the Lusitanian Basin are thus shown in a range, representing the above-mentioned scenarios. It should be underlined that these differ from the ones presented in Deliverable 5.2, which depict average representative values

Table 5-1 Industries with capture in Lusitanian Basin – Short term

Unit ID	E#01	E#02
Facility name	Centro de Produção de Souselas	Fábrica da Marinha Grande
Industry sector	Cement	Glass
2018 Reported emission (Mt/y)	0.89 (Fossil CO2)	0.09 (Fossil CO2)
Start Year	2028	2028
End Year	2038	2034
Efficiency	0.06	0.10
Annual capture rate (Mt/y)	0.058-0.064 (including CO_2 from biomass use)	0.02
Total CO_2 emitted if not captured (Mt)	0.79 - 0.89 (fossil CO_2)	0.09

5.1.3 Transport mode

The transport mode in the short-medium term is constituted by a train connection of around 80 km, that transports 0.05 Mt CO_2 /year from E#01 to E#02 and a pipeline connection with a total of 23 km to deliver the CO_2 to the storage location. At this stage this pipeline was split into four segments, each designed individually, because that configuration is more favourable for the long-term scenario transport needs. Total discounted costs for transport at this stage range between 12 M€ (DECARB) and 15 M€ (BAU).

5.1.4 CO_2 Utilization

In the short/medium term, around one-third of the CO_2 captured is used in greenhouses, which is a farming practice highly used in the agricultural sector of the Oeste NUTS III region, close to the CO_2 capture pilots of the Lusitanian Basin.

Table 5-2 CO_2 utilization in Lusitanian Basin in the short-medium term

CO_2 utilization	
Industry	Greenhouses
Product	Fruits and Vegetables
Quantities	----
Total CO2 used	0.22 Mt

Total revenues from CO2 used (discounted)	18 M€

5.1.5 Storage considered in the clusters

The values of the total CO_2 stored, in both the BAU and the DECARB pathways, are very similar (Table 5-3) because only a small amount of CO_2 resulting from the capture pilots of the glass and cement industries is being considered for storage between 2028-2034/2038. Consequently, the annual CO_2 flow for storage is low until 2035, with a constant injection of about 0.059 Mt/y and 0.062 Mt/y for the BAU and DECARB pathways, respectively. An increase in the storage volume is verified in 2035, with an annual injection flow of 2.77 Mt/y and 3.02 Mt/y for the BAU and DECARB pathways, respectively, marking the transition of the main scenario from the short/medium- to the long-term.

Considering the time span between 2028 and 2035, one CO_2 injector well is enough to store the CO_2 amounts predicted in both pathways. As the main scenario is defined in the onshore geological setting, most of the storage costs are associated with the OPEX component (including well maintenance and administrative costs), while the well drilling costs is the most relevant parameter in the CAPEX cost component. In addition to the CO_2 injector well, one monitoring well and one back-up well are also considered during this period and included in the total storage costs.

Table 5-3 indicates the total discounted storage costs with values ranging between about 88.8 M€, for the BAU pathway, and about 89.5 M€ for the DECARB pathway. It is important to mention that these values correspond to the storage discounted costs. These high storage costs result from the low CO_2 stored values during the period of the capture pilots that, despite these significative values of storage, would allow, not only for testing the capture infrastructure, but mainly to deepen the knowledge about the reservoir storage parameters (injectivity and storage capacity) provided through the CO_2 pilot injector well. This would be important in this early injection stage to confirm the feasibility studies of this storage unit and for decision-making for the subsequent injection stages.

Table 5-3 CO_2 storage in the Lusitanian Basin in the short-term

Unit ID	SU#01
Name & Location	S. Mamede & Onshore
Start date of storage	2028
End date of storage	2035
Total CO2 stored (Mt)	3.20 – 3.43
Total discounted costs (CAPEX + OPEX) (M€)	88.8 – 89.5
Total energy used (MWh)	1.60E+04 – 1.72E+04
Number of wells (injector, monitoring, back-up)	3

5.1.6 KPIs of the scenario

Due to its characteristics (pilot units), the KPI is not presented for the short term. Capture pilot CAPEX range between 22.8 M€ to 40 M€ for glass and cement facilities, respectively.

5.2 Lusitanian Basin: Main Long-term scenario 2050

5.2.1 Cluster(s) emissions before CCUS

As explained in 5.1.2 and Deliverable 5.2 [1], industries have been implementing mitigation strategies, which will induce a reduction of the CO_2 emissions in the short and long term. In some cases, e.g., emitter #8, this reduction may go up to around -20% comparing with 2018 values, while for others it represents a shift from fossil to CO_2 bioenergy emissions.

5.2.2 Emitters considered for capture technologylists the emitters considered for capture in the medium-long term, that is, the facilities in the glass, cement, lime and paper and pulp sectors emitting more than 80 kt CO2/y i (including biomass CO2 emissions).

Table 5-4 lists the emitters considered for capture in the medium-long term, that is, the facilities in the glass, cement, lime and paper and pulp sectors emitting more than 80 kt CO_2/y i (including biomass CO_2 emissions).

Table 5-4 Industries with capture in Lusitanian Basin – Long term

Unit ID	E#03	E#04	E#05	E#06	E#07	E#08	E#09	E#10	E#11	E#12	E#13	E#14	E#15
Facility name	Fábrica SECIL - Outão	Centro de Produção de Alhandra	Fábrica da Marinha Grande	Santos Barosa - Vidros, S.A	Industria Mineral - Prod Cales não Hidraulicas	Centro de Produção de Souselas	GALLOVIDRO, S.A.	Verallia Portugal, S.A.	Fábrica Maceira-Liz	Fábrica Cibra-Pataias	About The Future- Empresa Produtora de Papel S.A.	Celbi	Soporcel (Navigator Paper Figueira)
Industry sector	Cement	Cement	Glass	Glass	Cement	Cement	Glass	Glass	Cement	Cement	Paper and pulp	Paper and pulp	Paper and pulp
2018 Reported emission (Mt/y)	0.84 (fossil CO_2)	0.94 (fossil CO_2)	0.09	0.14 (fossil CO_2)	0.38	0.89 (fossil CO_2)	0.08 (fossil CO_2)	0.09	0.35 (fossil CO_2)	0.27 (fossil CO_2)	1.31 (fossil+bio CO_2)	1.04 (fossil+bio CO_2)	0.44 (fossil+bio CO_2)
CCU/CCS	CCU/CCS	CCU/CCS	CCU/CCS	CCS	CCS	CCU/CCS	CCS	CCS	CCU/CCS	CCU/CCS	CCU/CCS	CCU/CCS	CCU/CCS
Start Year	2035	2035	2035	2035	2035	2040	2040	2040	2045	2045	2045	2045	2045
End Year	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050
Efficiency	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.90	0.90	0.90
Annual capture rate (Mt/y)	0.99-1.04	1.13-1.17	0.19	0.29	0.52-0.54	0.72 -0.93	0.17	0.19	0.42-0.51	0.32-0.35	1.79-1.90	1.42	0.60
Remaining fossil CO2 emissions (Mt/y)	0.14-0.15	0.16-0.19	0.03	0.05	0.09-0.10	0.09-0.16	0.03	0.03	0.06-0.09	0.04-0.05	0.04-0.06	0.02	0.01
Total fossil CO_2 emitted if not captured (Mt)	0.74-0.84	0.83- 1.06	0.09	0.14	0.38	0.52-0.88	0.08	0.09	0.29-0.34	0.20-0.26	0.26-0.42	0.1	0.04

5.2.3 Transport mode

Transport for the long-term Main scenario is exclusively by pipeline. Both BAU and DECARB pathways share the same pipeline network structure. Properties for all the individual pipeline connections are presented in Table 5-5, while Figure 5-1 illustrates the pipeline network and some design proportions of the individual connections.

In total 20 pipelines are considered with a total length of around 310 km, to be deployed in four different time periods (around 23 km in 2028, 207 km in 2035, 62 km in 2040 and 18 km in 2045). Most of the single connections are small distance, composed by feeder pipelines. The five longer pipelines account for around 68% of the total length of the pipeline network.

In relation to annual volumes of CO_2 to be transported, pipelines are designed for the maximum annual amount that is expected to be transported, ranging from 0.2 to 4.6 Mt/year.

The total discounted costs, including the Short and Medium-term investment, are very similar for both pathways at around 115 M€ that represent unitary costs of around 0.1 to 2.6 €/ton with an average of 1.2€ per ton of CO2 transported from capture to storage.

Table 5-5 Pipeline CO_2 transport in the Lusitanian Basin in the long term.

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10
Total CO2 transported (Mt)	10.2 - 10.2	9.5 - 12.7	5.4 - 17.2	4.9 - 4.9	15.8 - 16.6	26.5 - 28	44.6 - 46.8	53.3 - 55.2	18.1 - 18.8	8.4 - 8.7
Max CO2 (tonCO2/y)	0.6 - 0.6	0.9 - 1.6	0.9 - 1.6	0.4 - 0.4	1 - 1	2.8 - 2.9	3.9 - 4.1	4.5 - 4.6	1.1 - 1.2	0.5 - 0.5
CAPEX (M€)	1.1 - 1.1	1.8 - 2.2	4.2 - 6.5	0.8 - 0.8	4.8 - 4.8	39.7 - 47.7	27.1 - 31.1	20.9 - 22	2.2 - 2.2	4 - 4
OPEX (M€)	0.4 - 0.4	1.2 - 1.9	2.6 - 4.5	0.2 - 0.2	1.7 - 1.7	16.7 - 19.6	12.5 - 13.7	10 - 10.8	0.7 - 0.7	1.4 - 1.4
Total cost (M€) (uncorrected-undiscounted)	1.5 - 1.5	3 - 4.1	6.8 - 10.9	1 - 1	6.5 - 6.5	56.5 - 67.2	39.6 - 44.9	30.9 - 32.8	2.9 - 2.9	5.4 - 5.4
€/tonCO2	0.1 - 0.1	0.3 - 0.3	0.6 - 1.3	0.2 - 0.2	0.4 - 0.4	2.1 - 2.4	0.9 - 1	0.6 - 0.6	0.2 - 0.2	0.6 - 0.6
M€/km	0.6 - 0.6	0.8 - 1.1	0.5 - 0.7	0.9 - 0.9	0.8 - 0.8	0.8 - 1	1 - 1.1	1.1 - 1.1	0.2 - 0.2	0.3 - 0.3
Distance (Km)	2.6	3.7	15.1	1.2	8.7	70.3	39.4	28.6	11.6	16.4
Total energy (GWh)	0 - 0	2.1 - 5.5	2.3 - 7.4	0 - 0	0 - 0	11.5 - 12.1	19.3 - 20.2	23.1 - 23.9	0 - 0	0 - 0
Average energy (MWh/y)	0 - 0	94 - 250	106 - 338	0 - 0	0 - 0	765 - 808	1287 - 1350	1537 - 1592	0 - 0	0 - 0

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Start year of scenario	2028	2028	2028	2028	2035	2035	2035	2035	2035	2035
End year of scenario	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050
Operation years	22	22	22	22	15	15	15	15	15	15

P P1	P16	P17		P		P1				
Total CO2 transported (Mt)	8 - 10.2	10 - 12.3	22.2 - 24.5	6.6 - 12.1	1.9 - 1.9	2.1 - 2.1	1.9 - 2.1	10.7 - 11.4	8.5 - 8.5	12.2 - 12.2
Max CO2 (tonCO2/y)	0.7 - 0.9	0.9 - 1.1	2.9 - 3.1	0.9 - 1.4	0.2 - 0.2	0.2 - 0.2	0.3 - 0.4	1.8 - 1.9	1.4 - 1.4	2 - 2
CAPEX (M€)	13.3 - 13.3	2 - 2.5	4.9 - 5.7	11.9 - 13.1	0.9 - 0.9	1.8 - 1.8	2.5 - 2.5	1.3 - 1.3	0.9 - 0.9	1.4 - 1.6
OPEX (M€)	3.5 - 3.5	0.8 - 0.8	2.4 - 2.5	5.2 - 5.3	0.1 - 0.1	0.4 - 0.4	0.3 - 0.3	0.1 - 0.1	0.1 - 0.1	0.4 - 0.5
Total cost (M€) (uncorrected-undiscounted)	16.8 - 16.8	2.8 - 3.3	7.3 - 8.2	17.1 - 18.4	1 - 1	2.1 - 2.1	2.8 - 2.8	1.5 - 1.5	1 - 1	1.8 - 2.1
€/tonCO2	1.6 - 2.1	0.2 - 0.3	0.3 - 0.3	1.5 - 2.6	0.5 - 0.5	1 - 1	1.3 - 1.5	0.1 - 0.1	0.1 - 0.1	0.1 - 0.2
M€/km	0.4 - 0.4	0.4 - 0.4	0.8 - 0.9	0.5 - 0.6	0.8 - 0.8	0.4 - 0.4	0.3 - 0.3	0.3 - 0.3	0.5 - 0.5	0.6 - 0.7
Distance (Km)	38.0	7.7	9.5	31.9	1.3	5.7	8.4	4.5	1.9	3.1
Total energy (GWh)	0 - 0	2.2 - 2.7	10.6 - 14.4	2.6 - 4.3	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	2.6 - 2.6
Average energy (MWh/y)	0 - 0	217 - 266	1058 - 1439	175 - 284	0 - 0	0 - 0	0 - 0	0 - 0	0 - 0	526 - 526
Start year of scenario	2040	2040	2040	2035	2040	2040	2045	2045	2045	2045
End year of scenario	2050	2050	2050	2050	2050	2050	2050	2050	2050	2050
Operation years	10	10	10	15	10	10	5	5	5	5

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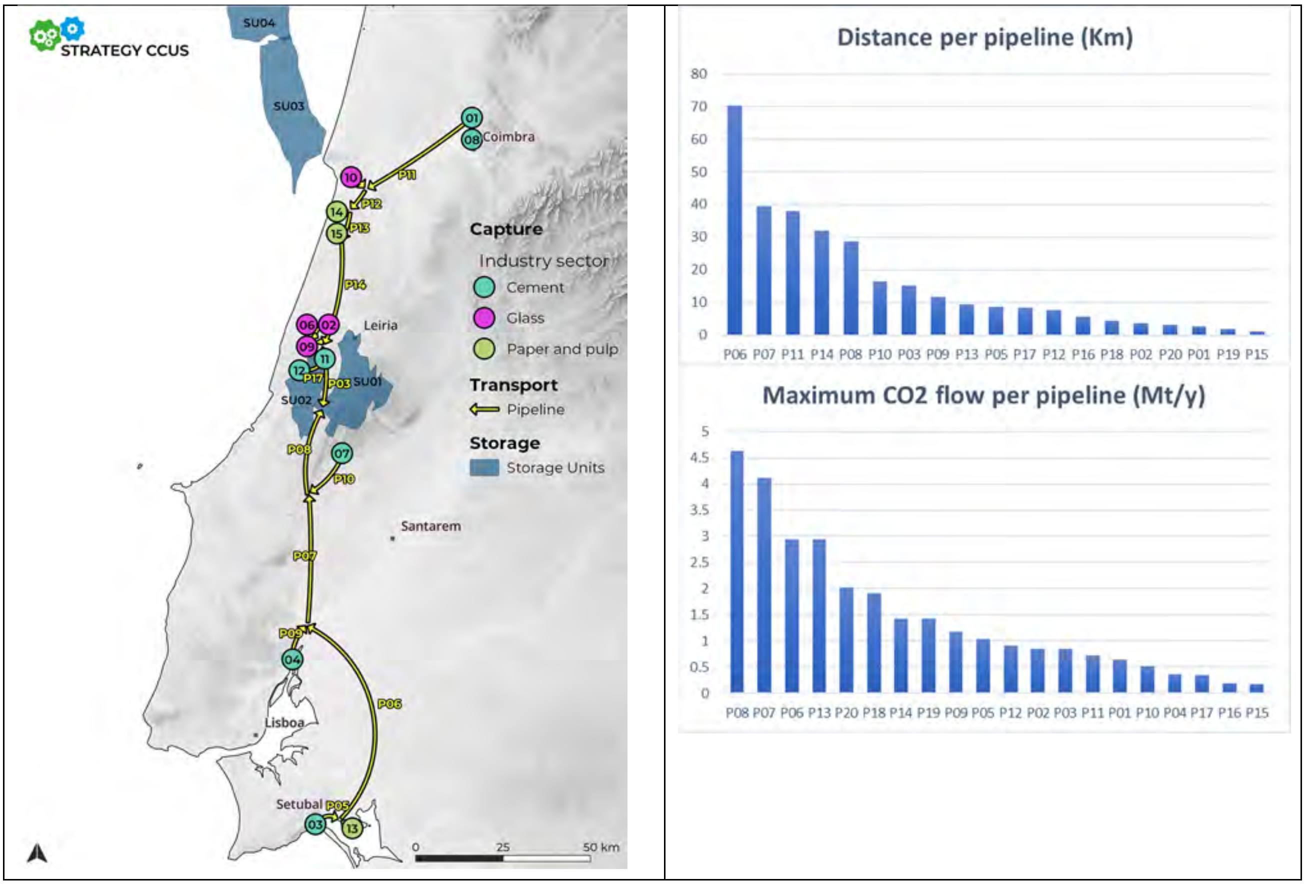
Figure 5-1 Pipeline network scheme (left), lengths and maximum CO_2 flow per year (DECARB pathway) (right).



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5.2.4 CO2 Utilization

According to the national Hydrogen Strategy (EN-H_2) and to support the national carbon neutrality goal, large amounts of CO_2 are needed to produce synthetic methane, which is used to decarbonize the Portuguese gas network. In the long term, all the CO_2 captured from bioenergy sources are thus used to generate synthetic methane (U#02) (Table 5-6). The generation of synthetic methane will possibly be at Carriço, – a location with salt caverns currently being used for natural gas storage and adequate for hydrogen and intermediate CO_2 storage. It should be underlined that the revenues presented in Table 5-6 are only linked to the use of CO_2 assuming a unitary price equal to EU-ETS. Additional economic benefits such as the reduction of natural gas imports are not considered, which can enhance the competitiveness of CO_2 use for methane generation. Likewise, the investments and operation cost of methanisation or the sales of methane are not accounted for.

Table 5-6 CO_2 utilization in Lusitanian Basin in the long term

CO2 utilization	
Industry	Synthetic Fuels
Product	Methane
Quantities	7.60 - 11.21 Mt methane
Total CO_2 used	21.89 - 32.27 Mt CO_2
Total revenues from CO_2 used (discounted)	2 642.5 – 3 857.8 M€

5.2.5 Storage considered in the clusters

In the Main long-term scenario (2035-2050), the CO_2 stored volumes increase substantially, requiring the distribution of CO_2 in an additional storage unit (SU#02) as indicated in Table 5-7.

The average values of CO_2 annual injection rates of the BAU and DECARB pathways are, respectively, 4.47 Mt/y and 3.82 Mt/y, ranging between 2.96 – 5.66 Mt/y (BAU) and 2.70 – 4.73 Mt/y (DECARB) for the minimum and maximum values of CO_2 injection rates. The maximum values of annual injection rate of each storage unit are about 3.07 Mt/y (SU#01) and 1.65 Mt/y (SU#02) for the DECARB pathway, and 3.02 Mt/y (SU#01) and 2.83 Mt/y (SU#02) for the BAU pathway.

In addition to the planned injector well for the short-medium-term scenario (SU#01), two injector wells are also planned to be drilled in the SU#01 (2035), for both BAU and DECARB pathways, and three in the SU#02 (2040) for the former (BAU) and two for the latter one (DECARB). The total number

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of planned wells for this long-term scenario is indicated in Table 5-7, including the monitoring and back-up wells previously mentioned for the SU#01 (before 2035), but also one additional monitoring well and one back-up well for the 10 years of the injection period in the SU#02.

Table 5-7 CO2 Storage in the Lusitanian Basin in the long-term

Unit ID	SU#01	SU#02
Name & Location	S. Mamede & Onshore	Alcobaça & Onshore
Start date of storage	2035	2040
End date of storage	2050	2050
Total CO2 stored (Mt)	41.10 – 43.77	16.20 – 23.30
Total discounted costs (CAPEX + OPEX) (M€)	242.3 – 254.5	
Total energy used (MWh)	1.87E+05 – 2.17E+05	8.11E+04 – 1.13E+05
Number of wells (injector, monitoring, back-up)	5	4 – 5

Considering the required number of planned wells, the total costs of the storage component increased, when compared to the short-medium-term scenario. Nonetheless, the annual stored volumes of CO_2 also increased significantly in the long-term scenario, impacting therefore in the total discounted costs (CAPEX + OPEX) as indicated in the Table 5-7. These costs correspond to the cumulative storage costs of both storage units between 2035-2050, ranging between 242.3 M€ and 254.5 M€ for the DECARB and BAU pathways, respectively.

5.2.6 KPIs of the scenario

The following pictures present the KPIs for the Main scenario, comprising the BAU and DECARB pathways emissions as explained in Section 4.1.1. **Overall, the whole CCUS chain can capture 93 Mt of the CO_2 emissions in the Lusitanian Region between 2035 and 2050, leading to 60-70 Mt of avoided emission** (comparing with 2018 values)**. The total CCS costs range between 62-72 €/ton of CO_2 avoided (discounted values), with CO_2 capture representing 90% of the value, followed by storage (8-9%) and transport (around 3%).**

The regional utilization of CO_2 (22 to 32.5 Mt of CO_2) linked to synthetic methane production corresponds from 66 to 77% of the national needs according to the National Hydrogen Strategy (EN-H2). This underlines the fact that additional capture sites and emitters in the country should be considered to significantly decarbonise the gas grid as set by the national policy. Long-term use of CO_2

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in mineralization could also be considered in this region under carbonation (e.g., concrete construction and C&DW/concrete fines), concrete curing or novel cements, but no estimations were made at this stage either in volumes or costs. However, should the technology be brought to scale in the Lusitanian Basin and the accounting methodologies well defined, CO_2 mineralization technologies could provide meaningful economic and environmental gains in the future.

By analysing the costs over time, we can conclude that the difference between the CCS costs with EU-ETS costs (in the absence of CCS) can range between -294.7 M€ (savings) to 348.4 M€ (costs). This means that besides its environmental advantages, the full CCS chain may also be economically positive when considering the underlying economic assumptions described in Section 2.2 (e.g., EU-ETS price from 46 €/ton CO_2 by 2021 to 250 €/ton CO_2 by 2050) and a conservative decarbonisation pathway for industries (Scenario BAU). These numbers should however be looked carefully as utilization costs and revenues are not being considered. Moreover, the costs in the absence of CCUS assume the 2018 reported emissions, which according to the decarbonisation plans of several industries may represent an overestimation of the EU-ETS emissions and costs. Additional analysis concluded that EU-ETS costs evolution between 85-285.5 €/t (2022-2050) lead to an equilibrium between the EU-ETS costs in the absence of CCUS and CCS costs for the scenario DECARB.

Figure 5-2 and Figure 5-3 depict the overall cost analysis of Main Long-term CCUS associated with BAU and DESCARB scenarios, respectively.

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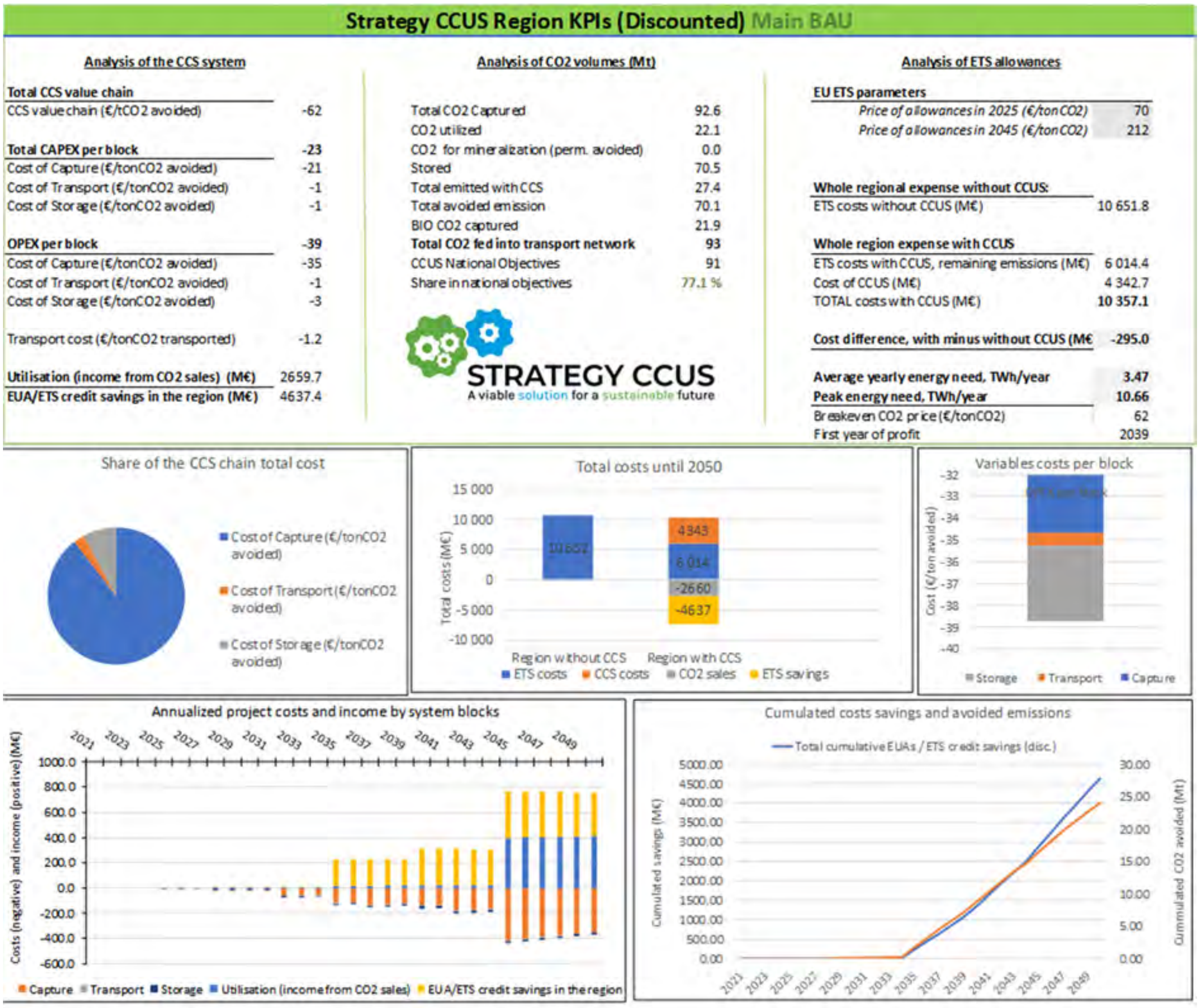

Figure 5-2 Overall cost analysis of the BAU scenario

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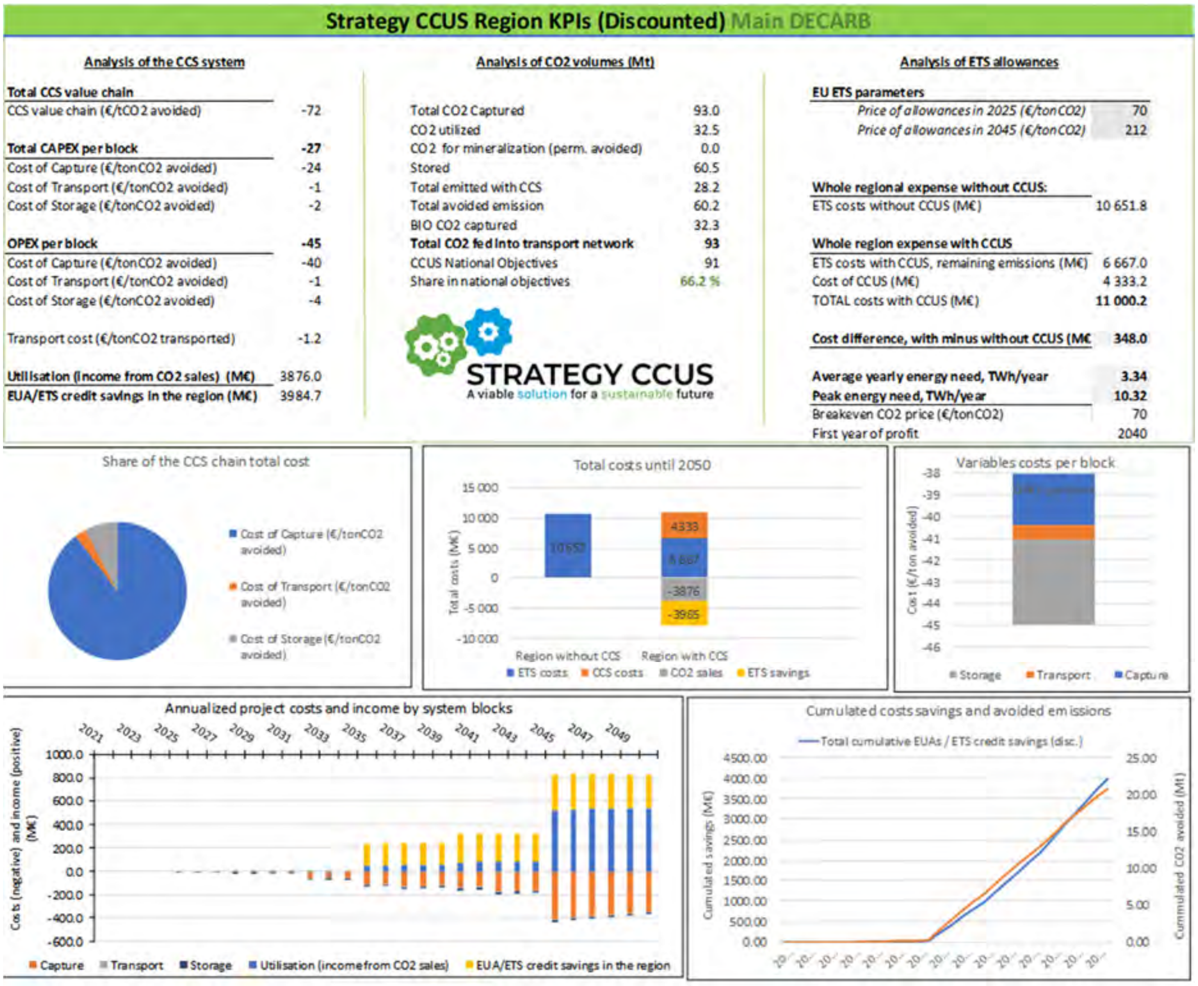

Figure 5-3 Overall cost analysis of the DECARB Pathway

5.3 Lusitanian Basin: Alternative scenarios

5.3.1 Difference with the Main scenario

To consider the risks and the possible low public acceptance of onshore storage, the alternative scenarios for the Lusitanian Basin **assume offshore geological storage of CO_2** in the Torres Vedras Group (Lower Cretaceous) or in the Silves Group (Upper Triassic). Both storage units are in the same geological setting of the basin, close to the Coast. They differ on the different properties of the storage complex, justifying these two alternative locations of offshore storage scenarios. The transport for the reservoirs may be made totally by pipeline or both pipeline and ship (from southernmost emitters) as explained in Deliverable 5.2. The combination of different storage and transport options resulted in

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four alternative scenarios (for the sake of simplicity this deliverable only shows two representative scenarios – ***Alt DECARB Offshore Pipeline SU3/TV*** **and** ***Alt DECARB Offshore pipeline/ship SU04/SLV*** and compares them with the Main DECARB ad BAU scenarios). There is no difference between the main and the alternative scenarios in terms of emitters with capture facilities and the respective CO_2 captured. The total quantities of CO_2 transported, stored and used are the same with exception of the amount of CO_2 transported by ship in Alt DECARB Offshore pipeline/ship SU04/SLV scenario, which corresponds to 44.6 Mt, with the remaining 48 Mt to be transported by pipeline.

5.3.2 KPIs of the Alternative scenarios

Figure 5-4 and Figure 5-5 depict the overall costs analysis of the two representative alternative scenarios. The cost of CCUS chain for the alternative scenarios (i.e., assuming offshore storage) range between 77 to 78 €/ton of CO_2 avoided (discounted), representing more 6 to 15€/ton of CO_2 compared with the onshore storage scenarios, which may significantly decrease de competitiveness of the CCUS. The biggest increase is linked to transport by both pipeline and ship, which can raise the transport prices 5 times compared with the onshore pipeline. In this alternative scenario (Alt BAU Ship/Pipeline) transport costs go up to 8€/ton CO_2 avoided compared to 2€/ton CO_2 avoided from the BAU scenario. Offshore storage also leads to additional costs, around 2 to 3 times higher when comparing to the onshore ones. The storage cost of the alternative scenarios range between 10-14€/ton CO_2 comparing with 5-6€/ton CO_2 of the main onshore scenarios. Although the total number of wells planned (injectors, monitoring and back-up) between the main onshore scenarios and the alternative offshore scenarios are the same (i.e., 9 and 10 wells for the DECARB and BAU, respectively), the most significant difference between the total storage costs is due to the higher drilling and completion costs for offshore wells [5] but also to the surface infrastructure costs (about 6 times more expensive for the offshore scenarios).

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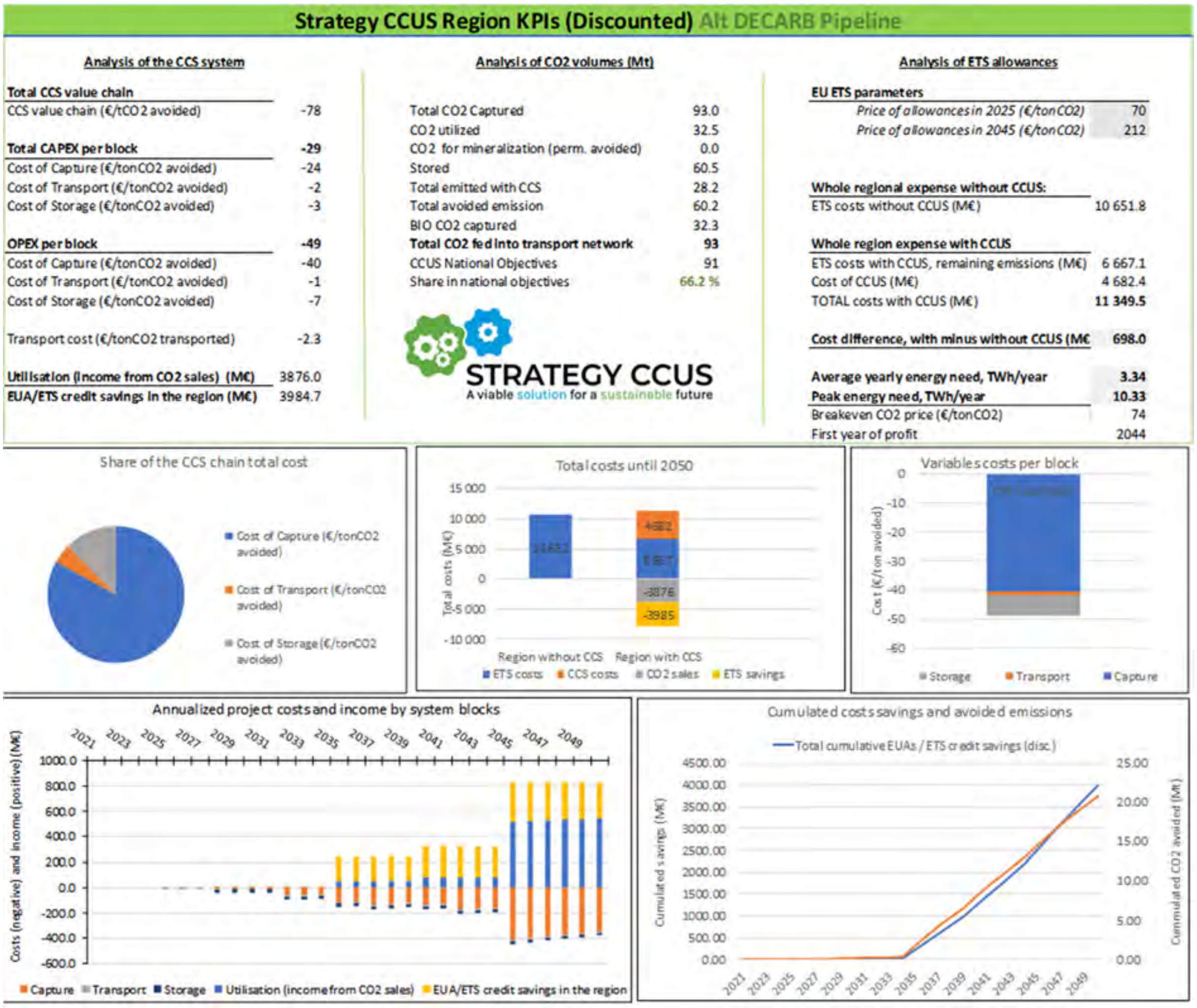

Figure 5-4 Overall cost analysis off the Offshore-TV-Pipeline for the DECARB pathway scenario

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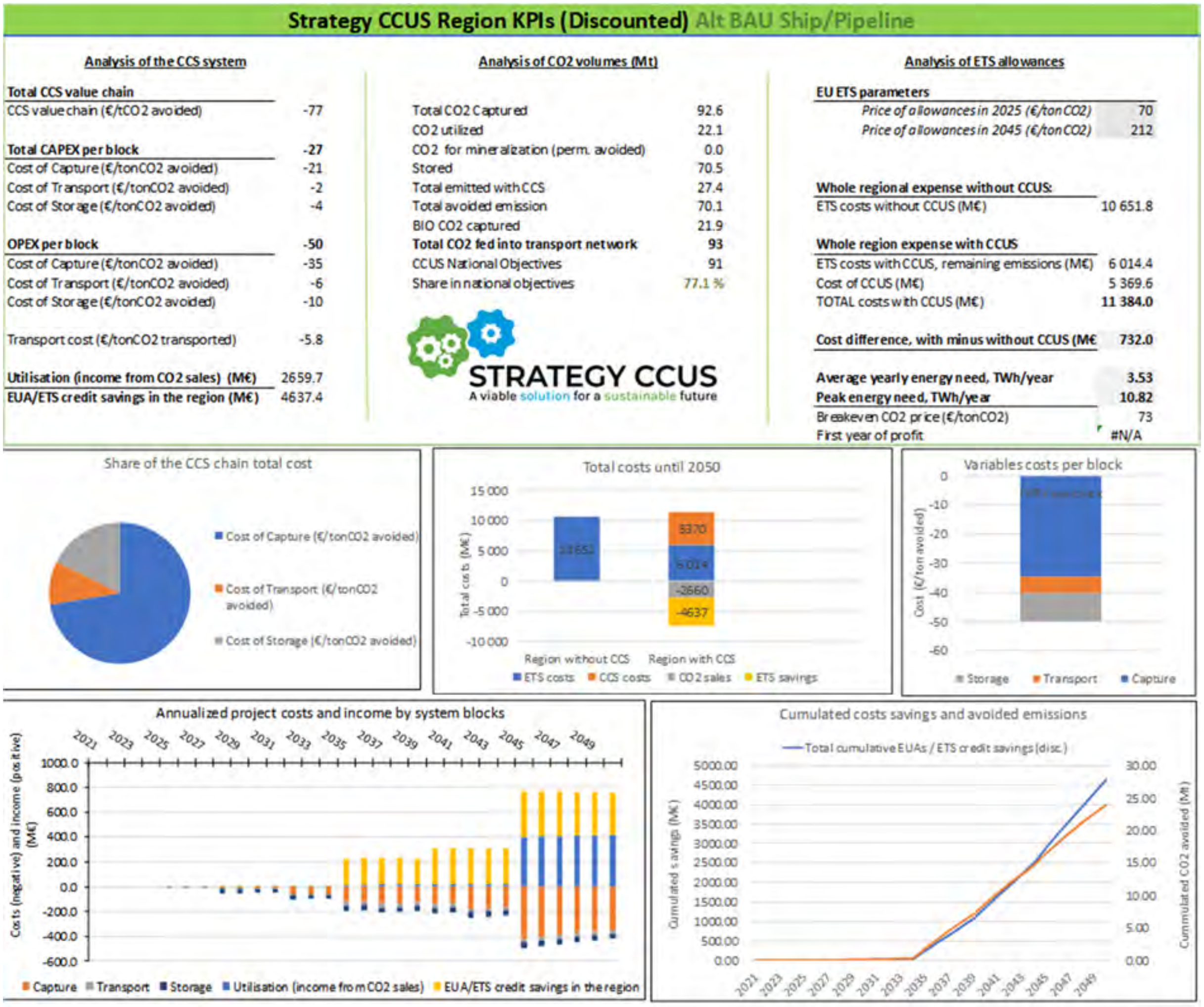

Figure 5-5 Overall cost analysis off the Offshore-SLV-Ship/Pipeline for the BAU scenario

The offshore drilling and completion costs were estimated based on reported literature values [5] for injector wells at similar water depths as those considered in the storage units of Portuguese CCUS scenarios.

5.4 Conclusion of the economic assessment of Lusitanian basin scenarios

In the short-medium term, it is not expected a full deployment of the technology in Portugal and in the Lusitanian Basin, and the scenarios abovementioned only comprise two pilot units in cement and glass industries. However, in the long term, after 2034, with a continued decrease of costs and a high implementation of the technology worldwide, **CCUS may be a relevant decarbonisation solution for**

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the specific industrial sectors in the Lusitanian Basin: cement, lime, glass and, at a later stage, paper and pulp due to bioenergy CO_2.

In Portugal, for the studied scenarios, CCUS costs can range from 62 to 78€/t avoided (discounted). Costs for the two onshore scenarios are 62 (BAU) and 72€ (DECARB) per ton avoided, with the difference mainly related to higher capture costs in the BAU scenario. The cost difference for the DECARB scenarios, 72€/t avoided in the onshore and 78€/t avoided for the offshore alternative, results mostly from higher transport and storage costs for the offshore alternatives (Table 5-8). Thus, and although it may present better public acceptance conditions, offshore storage leads to an increase from 8% to 24% of the overall CCS chain costs that may reduce its competitiveness. Despite this fact, CO_2 capture represents always the biggest share of CCUS costs, ranging from 72% to 90% of the total costs, which pinpoints the need for higher R&D on this component of the CCUS chain.

The capture scenarios designed for the Lusitanian Basin are supported by a series of assumptions which may have led to an augmentation of the total capture costs, such as the installation of the technology in glass and paper and pulp industries, with higher CAPEX than those shown in the literature for the power or the cement sectors. The scenarios assumed that almost all relevant fossil fuel emitters (>80kt/y) in the region may install carbon capture technology. However, alternative and more cost-effective decarbonization strategies for the glass industry may be available in the future, namely electric furnaces or the replacement of natural gas with hydrogen or other renewable gases. Moreover, CO_2 capture in paper and pulp industries is only justified by the existence of a bioCO_2 market for short term uses, as the generation of synthetic methane set in the current national Hydrogen Strategy.

These limitations and uncertainty suggest the development of an integrated technology analysis, covering CCUS and other alternative decarbonization technologies, which allows identifying the most cost-effective decarbonization options for each sector/industry and assessing the real competitiveness of CCUS.

The transport component is unlikely to be a limiting factor in the CCUS implementation in the region due to the low share of total costs in the CCUS chain. The pipeline network can be achieved with a great level of spatial optimization that can facilitate cost mutualization between stakeholders. This is a consequence of the favorable geographic distribution of the emitters, that allow for a backbone of larger, shared pipelines, with shorter feeder pipelines for each emitter. New pipeline routes were defined to achieve the transport network; however the outcome network has a profound spatial parallelism with the existing natural gas pipeline network, implying that the CO_2 dedicated pipelines can, in theory, with probable economic and environmental gains, be totally or partially implemented following the existing natural gas corridors.

The central location of the onshore storage units in relation to the emitters also provides good transport performance since it allows for shorter transport distances for most of the CO_2, with the furthest emitter being at around a pipeline distance 140 km of distance from the storage site. Even if

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considering the furthest offshore storage unit, the maximum transport distance, by pipeline, would be around 250 km.

In the offshore scenarios, ship transport would only reduce the total length of the pipeline network by 120 km, while doubling the overall cost per ton of CO_2 avoided and increasing the CO_2 transport distance from the southernmost emitters to around 300 km. Therefore, transport by ship can only be regarded as a realistic option due to its inherent flexibility, and if cost reduction results from improved ship transport logistics scenario and ship technology advancements. Otherwise, due to the relatively small distances involved, pipeline transport provides the most valuable solution either environmentally or economically when compared to transport by ship.

Table 5-8 Summary of the costs results for the main and alternative scenarios

	Main DECARB onshore	Main BAU onshore	Alt DECARB Offshore Pipeline SU3/TV	Alt BAU Offshore pipeline/ship SU04/SLV
Capture costs (€/t CO_2 avoided)	64.5	55.4	64.5	55.4
Transport costs (€/t CO_2 avoided)	1.9	1.6	3.6	7.6
Storage costs (€/t CO_2 avoided)	5.5	4.9	9.6	13.5
Total CCS value chain (€/tCO2 avoided – discounted values)	72	62	78	77

A strength of the scenarios analysed consists of the several options studied regarding the transport options and geological storage reservoirs, both onshore and offshore, allowing a more comprehensive techno-economic assessment of the possibilities and costs of implementing the technology in Portugal. On the other hand, this economic study of the scenarios would benefit from a sensitivity analysis of the various investment and operational parameters of the CCUS components due to several uncertainties, such as, for instance, the efficiencies of CO_2 capture technologies or the low maturity level of the storage resources (Tier 1 and Tier 2 for the offshore and onshore units, respectively). As an example, for the storage component, a sensitivity analysis should be carried out integrating the uncertainty in the geological and reservoir parameters to improve the understanding of the economic impacts in the presented CCUS scenarios.

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6 France: economic evaluation of two regions Paris Basin and Rhone Valley

6.1 Paris Basin economic evaluation

Contrary to the other regions studied in the STRATEGY CCUS project, the Paris basin region does not comprise carbon-intensive heavy industries, and the carbon emission sites are scattered throughout this populated region. However, some geological formations of this sedimentary basin could theoretically offer large storage capacities. The approach adopted in this report and in the D5.2 [1] **is to investigate how the region could benefit from these theoretical storage capacities**. Thus, the proposed scenarios and the analysis of the development of the CCUS are conducted at local/regional scale. In fact, it is not the intend to conduct site specific feasibility studies. In addition, the industries mentioned below did not commit in the work presented in this report.

The Main scenario elaborated in STRATEGY CCUS considers developing storage sites in the southern part of the region, in the Trias formations of the Paris basin, and capturing the CO_2 emitted by the 3 largest carbon emitters in South of Paris, as well as the CO_2 emitted by 4 smaller-scale emitters located on the route of carbon transport to the storage. Transport mode would be essentially pipelines. More details are available in D5.2 [1].

The following section directly presents the results of the economic analysis carried out for the long-term scenario (2050). Indeed, a short-term analysis is not meaningful in the case of the Paris basin, as most emitters belong to the waste-to-energy sector, which is currently not in the EU-ETS in France. An Alternative scenario is also proposed and evaluated in the second section 6.1.2 .

6.1.1 Paris basin Main Long-term scenario 2050

6.1.1.1 Cluster(s) emissions before CCUS

Emissions of CO_2 in the Paris basin amounts to 5.5 Mt/y (in 2019). For the period 2024-2050, the emission baseline scenario considers for the 7 sites in the scenario the same annual level than 2019 – or 2024 for E#02. The total CO_2 emitted baseline during this time frame would amount to 54 Mt.

6.1.1.2 Emitters considered for capture technology

An overview of the techno-economic results from the capture side is provided in the Table 6-1 below for the 7 industries considered in the scenario.

E#01 emitted 646 kt CO_2 in 2019. However, a large part of these emissions comes from a SMR unit and is already captured. Thus, no additional capture installation is planned. The annual quantity of CO_2 available for storage is estimated to 373 kt. Still, some costs for capture are considered (junction costs…) and are expected to be 10% of the theoretical capture costs for this plant.

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The waste-to-energy unit in Ivry-sur-Seine (E#02) emitted 572 kt. However, the plant will be replaced by 2024 by a new installation with reduced capacity. The annual carbon emissions are estimated to 300 kt/y.

E#03 is a waste-to-energy unit located in Issy-les-Moulineaux in a dense urban area. Thus, the technical feasibility of implementing a capture installation will be challenging.

During 2035-2050, on top of the 3 first emitters (E#01, E#02, E#03), CO_2 is captured from 4 additional industries located on the route between Ivry and the storage place. For emitters E#03, E#04, E#05, E#06 and E#07, we consider a captured rate of 85% of the CO_2 emissions, which is conservative number as capture technologies are rapidly improving.

Table 6-1 Industries with capture. Paris basin hub. Long term (2025-2050)

Industries with capture (2025-2050)		E#01 (FR1.ES.002)	E#02 (FR1.ES.003)	E#03 (FR1.ES.004)	E#04 (FR1.ES.012)	E#05 (FR1.ES.016)	E#06 (FR1.ES.018)	E#07 (FR1.ES.22)
Sector		Chemistry	Energy from waste	Energy from waste	Energy from waste	Energy from waste	Heat and power	Energy from waste
Location		Grandpuits	Ivry-sur-Seine	Issy-les-Moulineaux	Rungis	Créteil	Vitry-sur-Seine	Vert-le-Grand
Annual CO2 emissions considered – MtCO2/y		0.65	0.30	0.38	0.11	0.22	0.24	0.19
Capture start year		2027	2030	2032	2036	2037	2038	2036
Total CO2 captured	Total – MtCO2	8,5	5,7	6,2	1,3	2,6	3,0	2,4
	Incl. from biomass – MtCO2	0,0	2,8	3,1	0,7	1,3	0,0	1,2
Energy for capture (TJ)		-	24413	28255	6138	12066	14929	10928
Intermediate costs	CAPEX – M€	4,1	76,39	84,9	48,8	67,2	55,4	62,5

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(Undiscounted)	Fixed OPEX – M€	2,9	360,07	362,2	164,2	211,1	26,6	210,4
	Variable OPEX – M€	1,3	0,30	0,4	0,0	0,1	0,5	0,1
	Total costs - M€	8,3	436,76	447,5	213,0	278,4	82,6	273,0

Over the whole scenario duration, i.e., by 2050, **a total of 29.8 $MtCO_2$ is captured, including 9.1 Mt from biomass.** Indeed, 5 out of the 7 selected industries are waste-to-energy plants and half of the emissions of these plants are here estimated to be biogenic.

The Table 6-1 details CO_2 capture and associated costs for each of the 7 emitters. These costs are undiscounted. Considering economic factors such as inflation rate, decrease learning factor and discount rate, **final discounted costs for capture amount to 125.5 M€ for CAPEX and 602.8 M€ for OPEX. This corresponds, respectively, to 4.2 € and 20.3 € per ton of CO2 avoided for the whole long-term Main scenario**. The Table62summarises the global capture data and costs.

Table 6-2 Capture costs for Paris basin hub. Long term (2025-2050)

		TOTAL HUB
Annual CO2 emissions considered – MtCO2/y		62,7
Total CO2 captured	Total – MtCO2	29,8
	Incl. from biomass – MtCO2	9,1
Energy for capture	TJ	96728
	GWh	26871
Discounted costs	CAPEX – M€	125
	OPEX – M€	603
	Total costs - M€	728

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6.1.1.3 Transport mode

Transport of CO_2 is planned by pipelines essentially, connecting emitters to hubs and hubs to storage sites. New pipelines built on purpose for CO_2 transport are considered, as no possibility for reusing existing pipelines (gas, oil…) has been identified at this stage. However, the route of the new pipelines follows the existing ones to facilitate their implementation. The graph below (Figure 6-1) depicts the CO_2 network for Paris basin scenario: emitters, pipelines and hubs for CO_2 transport, and storage units.

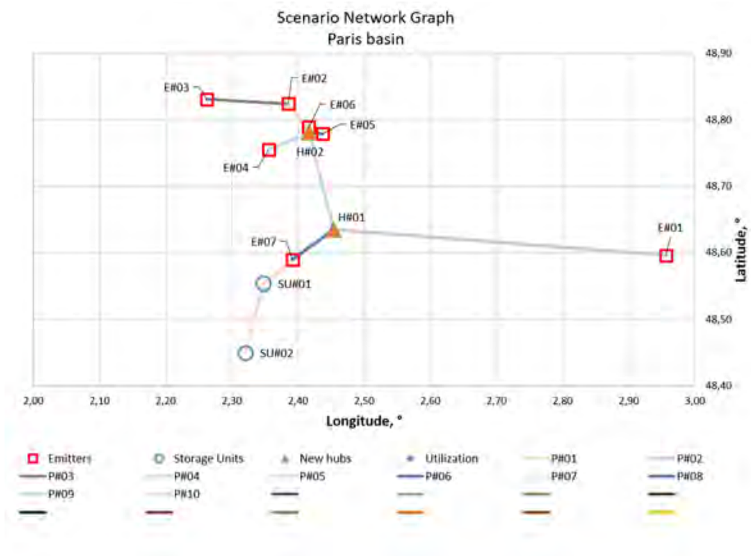

Figure 6-1: Graph of the Paris basin CO_2 network

Ten pipelines with a total length of 120 km are planned. Details for each pipeline and related undiscounted costs are provided in Table 6-3. **Total discounted costs for transport amount to 20.2 M€ for CAPEX and 9.4 M€ for OPEX. This corresponds, respectively, to 0.7€ and 0.3€ per ton of CO_2 avoided for the whole Main long-term scenario.**

Table 6-3 Transport pipelines. Paris basin hub. Long term (2025-2050)

Pipeline	Start point	End point	Start year	End year	Distance (km)	Diameter (mm)	Total CO2 transported Mt	Total undiscounted cost, €M
P#01	H#01	SU#01	2027	2050	14	178	29.81	8.51
P#02	E#01	H#01	2027	2050	41	114	8.52	13.62

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P#03	E#03	E#02	2032	2050	10	114	6.20	3.38
P#04	E#02	H#02	2030	2050	5	114	11.87	2.23
P#05	E#04	H#02	2035	2050	6	114	1.44	2.09
P#06	E#05	H#02	2037	2050	2	114	2.65	0.91
P#07	E#06	H#02	2037	2050	1	114	3.26	0.73
P#08	E#07	H#01	2035	2050	9	114	2.56	2.53
P#09	H#02	H#01	2030	2050	19	154	18.89	8.92
P#10	SU#01	SU#02	2035	2050	13	114	10.09	4.05

6.1.1.4 Storage considered in the clusters

Two storage sites are considered in the Paris scenario, both in the Keuper formation (Trias). The first storage SU#01 is initiated in 2027 to store CO_2 from the 3 first emitters. From 2036, an additional storage site, SU#02, is started as SU#01 does not have sufficient capacity to store CO_2 from the whole cluster (7 emitters). **By 2050, a total of 29.8 Mt should be stored. Total discounted costs for storage amount to 126.7 M€ for CAPEX and 284.9 M€ for OPEX. This corresponds, respectively, to 4.3€ and 9.6€ per ton of CO_2 stored** (see Table 6-4). Details for each storage site are provided in the Table 6-5 Storage sites features. Paris basin hub.

Table 6-4 Storage costs for Paris basin hub. Main Long-term scenario (2025-2050)

		TOTAL STORAGE	Cost per ton CO2 stored (€/t)
Total CO_2 stored	Total – MtCO2	29.8	
	Incl. from biomass – MtCO2	9.1	
Energy for storage	GWh	152.6	
Storage costs (Discounted)	CAPEX – M€	126.7	4.3
	OPEX – M€	284.9	9.6
	Total costs - M€	411.6	**13.9**

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Table 6-5 Storage sites features. Paris basin hub

Storage	SU#01	SU#02
Storage Unit ID	FR1.SU.001	FR1.SU.003
Formation	Keuper (Trias)	Keuper (Trias)
Name	Chailan	Grès intermédiaire
Localisation	48,553526 - 2,347636	48,449553 - 2,320551
Depth (m)	2014	2216
Reported capacity (Mt)	29.5	32.4
Start injection year	2027	2036
End year	2050	2050
Number of wells by 2050	2	1
Total CO2 stored (Mt)	20.39	9.42
Total CO2 emitted (Mt)	0.10	0.05
Total energy used (MWh)	1.05E+05	4.79E+04

6.1.1.5 KPIs of the scenario

The Tool developed in the STRATEGY CCUS project for economic assessment of the scenarios provides selected Key Performance Indicators (KPIs). The CCUS value chain of the scenario is calculated in terms of €/t of CO_2 avoided. Table 6-6: KPIs of the main scenario for the Paris basin Region below summarises the results of the Paris basin scenario concerning costs of the CCS value chain - broken down into CAPEX/OPEX, capture/transport/storage (see also graph in Figure 6-2 – and balance of CO_2 volumes – captured, emitted, etc., also depicted in Figure 6-2). The energy costs for the CCS value chain are considered in terms of TWh/year using current costs of electricity and its evolution for 2050. The average energy needs are provided in Table 6-7.

The French Low Carbon Strategy (SNBC 2) presents scenarios where CCUS should take part to emissions reductions of around 5 Mt/y in the industry sector and 10 Mt/y for BECCS by 2050. The cumulated amount of CO_2 to be stored by 2050 is then not provided. An estimated quantity of 320 Mt has been taken, in accordance with Rhone valley scenario (page 70), which would correspond to an average yearly rate of 12 Mt/y.

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In the Paris basin scenario, 5 emitters belong to the waste industry, with a total of 18.2 Mt CO_2 captured by 2050. This includes 9.1 Mt CO_2 from biomass. From 2037 (year when all 5 waste-to-energy plants have installed capture) until 2050, the yearly quantity of CO_2 captured is 1.35 Mt/y, including 0.67 Mt/y from biomass. If the waste-to-energy sector is considered as BECCS by SNBC, the Paris basin scenario could contribute to 7% of the BECCS objectives for 2050.

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Table 6-6: KPIs of the main scenario for the Paris basin Region

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-39,4
Total CAPEX per block	-9,2
Cost of Capture (€/tonCO2 avoided)	-4,2
Cost of Transport (€/tonCO2 avoided)	-0,7
Cost of Storage (€/tonCO2 avoided)	-4,3
OPEX per block	-30,2
Cost of Capture (€/tonCO2 avoided)	-20,3
Cost of Transport (€/tonCO2 avoided)	-0,3
Cost of Storage (€/tonCO2 avoided)	-9,6
Transport cost (€/tonCO2 transported)	-1,0
Utilisation (income from CO2 sales) (M€)	0,0
EUA/ETS credit savings in the region (M€)	2581,2

Analysis of CO2 volumes (Mt)

Total CO2 Captured	29,8
CO2 utilized	0,0
CO2 for mineralization (perm. avoided)	0,0
Stored	29,8
Total emitted with CCS	10,4
Total avoided emission	29,7
BIO CO2 captured, neg. Emissions	9,1
Total CO2 fed into transport network	**30**
CCUS National Objectives	320
Share in national objectives	9,3 %

STRATEGY CCUS
A viable solution for a sustainable future

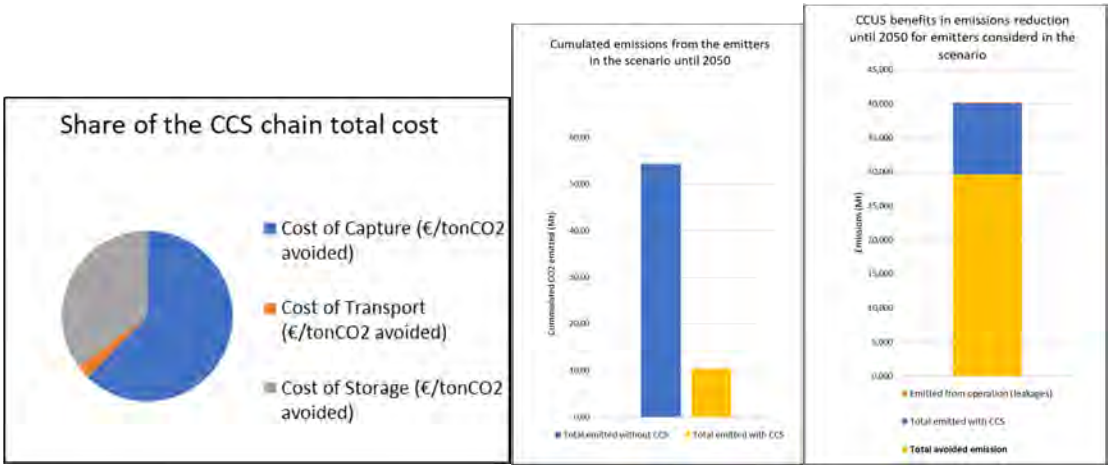

Figure 6-2 Share of Capture, Transport and Storage in the total cost. Paris basin main scenario; Comparison of CO2 emissions with and without CCS. Paris basin main scenario; Emissions reduction with CCS. Paris basin main scenario

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Table 6-7: Energy need for CCS value chain. Paris basin main scenario.

Total energy need		
Average yearly energy need, TWh/year	1,04	
Peak energy need, TWh/year	1,62	

The analysis of ETS allowances performed in the others STRATEGY CCUS regions is not relevant in the case of the Paris basin. Indeed, only E#01 and E#06 are in this system. In France, the waste-to-energy plants are not in the EU-ETS.

6.1.2 Paris basin Alternative scenario

6.1.2.1 Difference with the main

The alternative scenario for Paris basin region differs from the Main scenario essentially on the storage site. **A new storage site is planned** in the vicinity of E#01. There is less knowledge on potential capacity of this reservoir than on the storage units considered for the Main scenario. However, being closer to one of the emitters, this location would reduce transport and facilitate the start-up of the CCS chain. In this Alternative scenario, only one storage site is planned to store the total amount of the emissions from the 7 industries on the 2050-term. The emitters considered in the Alternative scenario are the same than the ones in the Main scenario. As in the Main scenario, new pipelines are planned to transport CO_2. There are some changes in the pipelines routes since the storage location has changed, but most of the sections stay the same. The graph below (Figure 6-3) depicts the CO_2 network for the alternative scenario.

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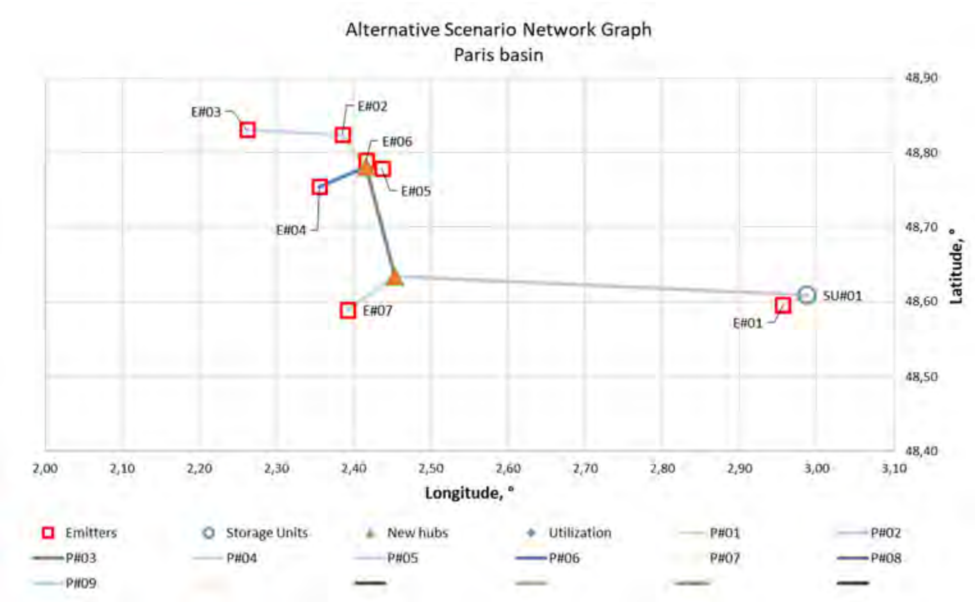

Figure 6-3 Graph of the Paris basin CO_2 network. Alternative scenario

The CO_2 transport network in the alternative scenario comprises 9 pipelines, with a total length of 114 km. Total discounted costs for transport amount to 19.4 M€ for CAPEX and 8.7 M€ for OPEX. This corresponds, respectively, to 0.6€ and 0.3€ per ton of CO_2 avoided. **Transport costs are slightly reduced compared to the main scenario.**

Contrary to the storage units of the main scenario that are in the Keuper formation, the considered reservoir for Alternative scenario is in the Dogger formation (younger and less deep) made up of carbonate rocks (limestones). **Not much mature data on CO_2 storage capacities is availabl**e for this formation. However, a lot of knowledge on this aquifer of the Paris basin is available, as it has been exploited for hydrocarbons for decades and is still being exploited for geothermal. Features of the Dogger storage unit are gathered in the Table 6-8. Storage costs are noticeably reduced compared to the main scenario.

Table 6-8 Storage. Paris basin alternative scenario

Storage	SU#01
Storage Unit ID	FR1.SU.A
Formation	Dogger (Jurassic)
Name	Bathonian
Localisation	48,608985- 2,986947

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Depth (m)	1750
Reported capacity (Mt)	165.4
Start injection year	2027
End year	2050
Number of wells by 2050	3
Total CO2 stored (Mt)	29.8
Total CO2 emitted (Mt)	0.15
Total energy used (MWh)	1.53e5
Total costs (discounted) M€	289.8
Cost per ton CO2 stored (discounted) €/t	9.7

6.1.2.2 KPIs of the Alternative scenario

Compared to the Main scenario, the **Alternative scenario results in lower costs**, with a cost of total CCS value chain of 35.3€/tCO_2 avoided (compared to 39.4€/tCO_2 avoided in the main scenario). This is due to a decrease in transport costs, as well as in storage costs (only one site), for a same quantity of CO_2 captured. Capture costs and analysis of CO_2 volumes stay the same.

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Table 6-9: KPIs of the alternative scenario for the Paris basin Region

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-35,3
Total CAPEX per block	**-8,1**
Cost of Capture (€/tonCO2 avoided)	-4,2
Cost of Transport (€/tonCO2 avoided)	-0,7
Cost of Storage (€/tonCO2 avoided)	-3,2
OPEX per block	**-27,2**
Cost of Capture (€/tonCO2 avoided)	-20,3
Cost of Transport (€/tonCO2 avoided)	-0,3
Cost of Storage (€/tonCO2 avoided)	-6,6
Transport cost (€/tonCO2 transported)	-0,9
Utilisation (income from CO2 sales) (M€)	0,0
EUA/ETS credit savings in the region (M€)	2581,2

Analysis of CO2 volumes (Mt)

Total CO2 Captured	29,8
CO2 utilized	0,0
CO2 for mineralization (perm. avoided)	0,0
Stored	29,8
Total emitted with CCS	10,4
Total avoided emission	29,7
BIO CO2 captured, neg. Emissions	9,1
Total CO2 fed into transport network	**30**
CCUS National Objectives	320
Share in national objectives	9,3 %

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6.1.3 Discussion

The KPIs of the scenarios presented above have to be understood as the result of an analysis, including the whole CCS chain (7 emitters, transport, storage) on the long term with 25 years duration. Carried out at the regional scale, this study is not meant to be a site-specific feasibility study. Costs of the CCS chain for the Paris basin scenario are lower than those available in literature. This explains by the scale of the study and the duration of the scenario. Also, CAPEX has been annualized, leading to a decrease of the costs on a given timeframe. Finally, this analysis mutualizes all the costs, including the capture costs. It is also economically interesting to include the 4 smaller emitters in the long term. A test with only the 2 largest WtE plants results in total costs around 70€/t.

Waste-to-energy sector holds an important place in the Paris basin scenario, with 5 out of the 7 considered emitters being incineration plants. In line with the EU objectives, France follows a waste reduction policy which results in a decrease of the number of incineration plants. However, quantity of waste did not decrease in the two last decades. Thus, including WtE plants in CCUS scenarios by 2050 makes sense. Currently, 2 starting carbon capture projects in Europe target WtE plants: Twence in the Netherlands and Klemetsrud in Norway, showing the feasibility of capture system on incineration plants. Yet, implementing carbon capture on Paris basin WtE plants is still challenging, in terms of space needed for building a capture installation in dense urban areas, and in terms of energy needs as co-produced energy is already valorized (heating networks…). However, the CCS for Paris

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basin WtE plants could drastically reduce the CO_2 emissions of this area and provide negative emissions following the SNBC (French national low carbon strategy) guidance.

Unlike other European countries, France does not include the waste-to-energy (WtE) plants in the ETS. The analysis of ETS allowances performed by the STRATEGY CCUS Tool is not fully relevant in the case of the Paris basin. However, as discussions are ongoing to include WtE sector in the EU-ETS in the coming years, these results could provide insights for a hypothetical scenario where WtE plants would be subject to EU-ETS. They are provided in the following table for information purpose only.

Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	212
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	3 566,9
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	985,7
Cost of CCUS (M€)	1 169,3
TOTAL costs with CCUS (M€)	**2 154,9**
Cost difference, with minus without CCUS (M€)	**-1 412,0**
Average yearly energy need, TWh/year	**1,04**
Peak energy need, TWh/year	**1,62**
Breakeven CO2 price (€/tonCO2)	42
First year of profit	2028

Table 6-10: Indicative analysis of ETS allowances in the case waste-to-energy plants were in ETS for the scenario duration (Main scenario)

However, the inclusion of WtE facilities in EU-ETS is economically unfeasible today in France without a review of current and future taxes applied to WtE plants as a public service. In particular, the TGAP (General tax for polluting activities) is an important tax concerning the ton of incoming waste received in the facilities for storage and incineration processing of non-dangerous waste.

The slightly reduced costs resulting from storing CO_2 in the Dogger formation in the Grandpuits area, close to the highest emitter in the Paris Basin Region, could be in favour of the Alternative scenario compared to the Main when dealing with developing a CCS pilot-scale in Paris basin. A CCS pilot-scale project would demonstrate to local and national stakeholders the feasibility and the environmental impact of the CCS technology in terms of reducing emissions and associated risks.

6.1.4 Conclusion of the economic assessment of Paris basin scenarios

Economic analysis of the Paris basin scenarios results in costs for the CCS chain around 35-39€/tCO_2 avoided, which is promising for the development of CCUS in the region.

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CCS should be considered as a regional scale option for decarbonisation of industries; however, a more in-depth and detailed analysis needs to be conducted to validate these results obtained from the literature [8].

At the perspective of reducing CO_2 emission in the Paris Basin Region, the deployment of CCS should be considered, in particular in the Waste-to-Energy sector. However, nowadays, at site-scale, WtE installations lack of economic incentives to consider CCS. A political and financial support from the authorities, as it is the case in the Netherlands and in Norway, would be needed to develop CCUS as a solution for decarbonizing the region.

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6.2 Rhone Valley economic evaluation

6.2.1 Rhone Valley Main Scenario (short- and medium-term)

6.2.1.1 Clusters emissions before CCUS

Industrial CO_2 emissions in Rhône Valley identified as part of WP2 of the STRATEGY CCUS project are 18.6 Mt in 2018. Four industrial clusters are pointed out: Lyon, Montélimar, Beaucaire and Marseille from North to South. Marseille cluster is responsible for 58% of these emissions, or 10.8 Mt of CO_2.

In view of the large share of Marseille cluster CO_2 emissions on the one hand, and of the geographical distribution of emitting industries in this cluster on the other hand, **5 industrial sites near Fos-sur-Mer are considered for CO_2 capture** in the main scenario for short and medium-terms. CO_2 emissions of these sites were 9.3 Mt in 2018. CO_2 emissions of these 5 sites represent 86% of Marseille cluster emissions, and 50% of those of Rhône Valley. **Given the CCUS roadmap hereafter described, 26.3 Mt of CO_2 would be captured in the medium-term (2026-2039) by equipping these sites.**

6.2.1.2 Emitters considered for capture technology

Emitters considered for capture are presented in Table 6-11. There are less than fifteen kilometres between these sites, except for LafargeHolcim cement plant of La Malle which is around 35 kilometres from the other sites as the crow flies (65 kilometres approximately by train).

Table 6-11 Industries with capture in Rhône Valley in the short and medium terms

Unit ID	E/U#01	E#02	E#03	E#04	E#05
Facility name	ArcelorMittal FOS [1]	Petroineos Manufacturing France SAS [7]	AIR LIQUIDE HYDROGENE SMR Lavéra [	Kem One Lavéra [	LAFARGEHOLCIM CIMENTS [8] - USINE de La Malle
Industry sector	Iron & Steel	Refining	Hydrogen	Chemicals	Cement
2018 Reported emission (Mt/y)	7,46	1,21	0,18	0,07	0,43
CCU/CCS	CCU	CCS	CCS	CCS	CCS
Start Year	2026	2030	2030	2030	2030
End Year	2039				

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Efficiency	80%				
CO2 Capture rate (%)	10%	48%	80%	20%	38%
CO2 captured (Mt/y)	0,75	0.58	0.14	0.01	0.16
Total CO2 emitted if not captured (Mt)	18.65	12.20	1.56	0.28	3.44

6.2.1.3 Transport mode

There are about 50 km as the crow flies between the location of CO_2 storage considered from 2030 to 2039 in Les Saintes-Maries-de-la-Mer and the focussed Fos-sur-Mer industry hub. But this lies in Camargue (a wetland protected coastal site). It is then preferred to transport the CO_2 by ship.

The CO_2 captured in LafargeHolcim cement plant located in Septème-les-Vallons is carried to Fos-sur-Mer by train as illustrated in Table 6-12. Pipelines are considered to carry CO_2 from other sites to the liquefaction point.

Table 6-12 Transport mode in Rhône Valley main scenario in the short and medium term

Transport mode	Pipelines	Train	Ship
From	Within a dozen km around Fos-sur-Mer	Septème-les-Vallons	Fos-sur-Mer
To		Fos-sur-Mer	Les Saintes-Marie-de-la-Mer
Distance		65 km	Approximately 75 km by boat (42 km as the crow flies)
Total CO_2 transported	11.2 Mt	2.7 Mt	13.9 Mt
CAPEX	12.3 M€	10.8 M€	174.4 M€
OPEX	2.6 M€	9.0 M€	129.9 M€
Total costs (uncorrected-undiscounted)	14.9 M€	19.8 M€	304.3 M€
€/ton CO_2	1.3	7.3	21.9

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M€/km	0.36	0.305	4.06

The costs associated with conditioning facility[7] are neglected, as well as the cost of docks building in les Saintes-Marie-de-la-Mer.

6.2.1.4 CO_2 Utilization

When scenarios are built, the multinational iron and steel producer ArcelorMittal has its sights on converting CO_2 into 60 ktpy of ethanol, as fuel or solvent, at its Fos-sur-Mer plant [14].

The CAPEX of Fos-sur-Mer plant is based on the 150 million euros ArcelorMittal invested in its Ghent site (Belgium) where the same process is in place to produce 80 million litres of ethanol [13]. Thus, the CAPEX for the Fos-sur-Mer plant is assumed to be 145.5 million euros[8].

Table 6-13 CO_2 utilization in Rhône Valley

CO_2 utilization	
Industry	ArcelorMittal steel plant in Fos-sur-Mer
Product	Ethanol
Quantities	60 ktpy of ethanol
Total CO_2 used	11.4 Mt globally from 2026 to 2039 (21.1 Mt from 2026 to 2050 - 17.9 Mt from steel production + 3.2 Mt from energy consumed for CO_2 capture)
EU ETS credit savings	1 410 M€ over 2026-2029 period

[7] One conditioning facility is at least needed within the Fos-sur-Mer industry hub to purify CO_2 coming from emitters located within a dozen-kilometre radius (E#02 to E#04), provided the pipelines connecting the capture facilities to the conditioning facility are compatible with raw captured CO_2 rich streams.

8 CAPEX for Fos-sur-Mer plant is calculated using the formula CAPEX1/CAPEX2 = $(\text{Volume1}/\text{Volume2})^{0.6}$

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6.2.1.5 Storage considered in the clusters

The storage site considered for the short and medium-term main scenario is in Les Saintes-Maries-de-la-Mer (Camargue). With a capacity of 13.9 Mt, it should be used until mid-2039 considering 2030 as in-service year.

Table 6-14 Storage considered in the short and medium terms main scenario for Rhône Valley

Storage	
Localisation	Les Saintes-Maries-de-la-Mer
Start date of storage	2030
End date of storage	2039
Total CO_2 stored	13.9 Mt
Cost of Storage	9.3 €/ton CO_2 avoided
Number of wells	2 (1 injector well + 1 monitoring well)

6.2.1.6 KPIs of the scenario

The short and medium terms main scenario for Rhône Valley covers the 2026-2039 period. This time window is considered because the Camarguese storage selected in Les Saintes-Maries-de-la-Mer, with a capacity of 13.9 Mt, is full during 2039 in view of the CCUS roadmap here presented.

25.3 Mt of CO_2 is captured over this period, of which 13.9 Mt are stored and 11.4 Mt are converted to produce ethanol.

The cost of CCUS chain is 36 €/ton of CO_2 avoided (discounted), with CO_2 capture representing the biggest part of costs (49%), before transport (26%) and storage (25%). Discounted CCUS costs are 526 M€.

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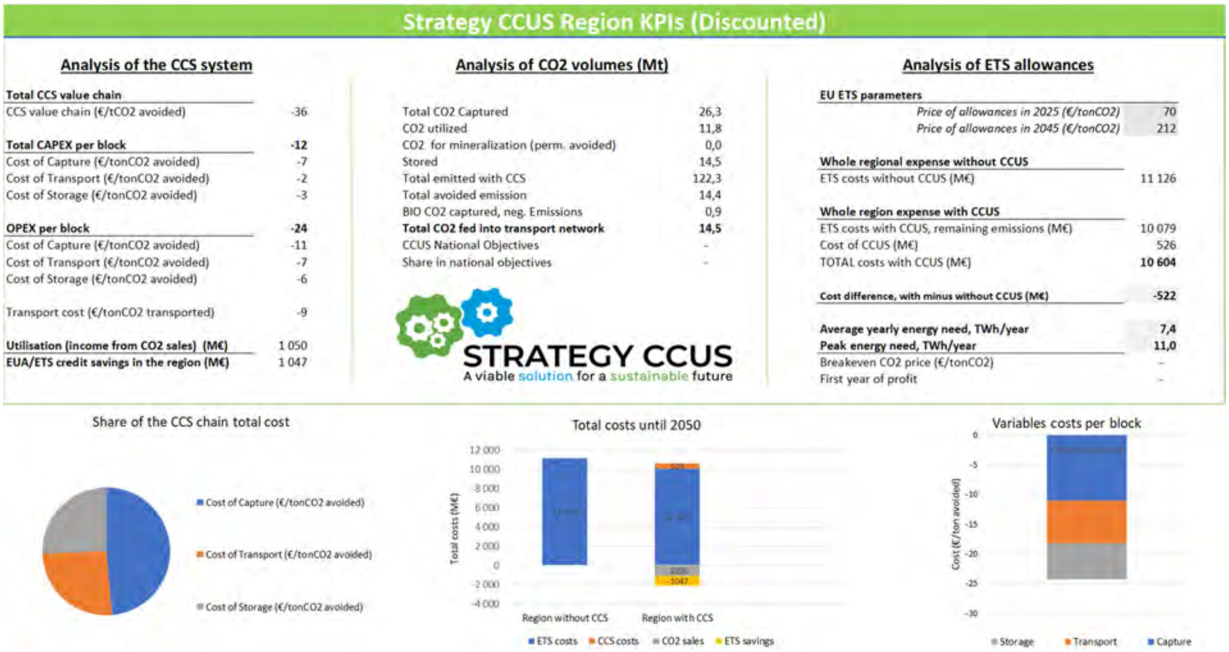

Figure 6-4 Overall cost analysis off the CCUS chain in Rhône Valley main scenario in the short and medium terms

6.2.2 Rhone Valley Main Long-term scenario

6.2.2.1 Cluster(s)r emissions before CCUS

Refer to 6.2.1.1

6.2.2.2 Emitters considered for capture technology

The EveRé energy from waste plant located in Fos-sur-Mer is added to the list of emitters considered for CCUS in the short and medium-terms main scenario (refer to Table 6-15). Capture is planned from 2040 in view of the maturity of CO_2 capture technologies in the waste incineration sector which is prima facie less advanced than other industries. The quantity of captured CO_2 on this site is 0.43 Mt over the 2040-2050 period.

Air Liquide SMR is considered shutdown in 2040. This shutdown is motivated by the decarbonation wave of industrial hydrogen in motion.

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Table 6-15 Industries with capture in Rhône Valley in the long-term main scenario

Unit ID	E/U#01	E#02	E#03	E#04	E#05	E#06
Facility name	ArcelorMittal FOS	Petroineos Manufacturing France SAS	AIR LIQUIDE HYDROGENE SMR Lavéra	EVERE [9]	Kem One Lavéra	LAFARGEHOLCIM CIMENTS - USINE de La Malle
Industry sector	Iron & Steel	Refining	Hydrogen	Energy from waste	Chemicals	Cement
2018 Reported emission (Mt/y)	7.46	1.21	0.18	0.40	0.07	0.43
CCU/CCS	CCU		CCS			
Start Year	2026	2030	2030	2040	2030	2030
End Year	2050	2050	2040	2050	2050	2050
Capture efficiency		80%				
CO_2 Capture rate (%)	10%	48%	80%	11%	20%	38%
CO_2 captured (Mt/y)	0,75	0.58	0.14	0.04	0.01	0.16

In this scenario, 50.5 Mt of CO_2 is captured within these sites over the 2026-2050 period.

6.2.2.3 Transport mode

The storage site considered for the short and medium terms main scenario in Les Saintes-Marie-de-la-Mer being full in mid-2039, an opportune Triassic storage site in the Paris Basin located near Puiseaux in the department of Loiret (Paris basin) is next considered.

The reuse of existing pipelines to transport CO_2 from Fos-sur-Mer to Puiseaux is preferred to minimize costs. A blanketed oil pipeline links Fos-sur-Mer to Karlsruhe (Germany) and can be

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reassigned to transport CO_2 in gaseous form from Fos-sur-Mer to the northeast quarter of France. It is chosen to reuse it from Fos-sur-Mer to Saint-Amour, a town in the department of Jura served by both rail and gas networks. The gas network is then preferred to carry CO_2 from Saint-Amour to Puiseaux from mid-2039.

It seems there is no incompatibility to convert this oil pipeline into CO_2 pipeline in terms of metallurgy and CO_2 flowrate[9]. Also, it seems there is no need to install compressor station with regards to elevation if this pipeline is partially reused to carry CO_2 in its first 360 kilometres.

On the basis that this oil pipeline is reassigned for CO_2 transport, the maximum permissible CO_2 flowrate is likely to be in line with the one accepted by the gas network[10] that feeds Paris basin. **The reuse of existing oil and gas pipelines (provided the latter are available) to carry CO_2 captured in Rhône Valley and to store it in Paris Basin should therefore go hand in hand with no investment virtually**.

Table 6-16 Transport mode in Rhône Valley for the long-term main scenario

<table>
<tr><th>Transport mode</th><th>Pipelines</th><th>Train</th><th>Ship</th><th>Existing oil pipeline</th><th>Existing gas pipelines</th><th>Pipeline</th></tr>
<tr><td>From</td><td rowspan="3">Within a dozen km around Fos-sur-Mer</td><td>Septème-les-Vallons</td><td>Fos-sur-Mer</td><td>Fos-sur-Mer</td><td>Saint-Amour</td><td>Puiseaux</td></tr>
<tr><td>To</td><td>Fos-sur-Mer</td><td>Les Saintes-Marie-de-la-Mer</td><td>Saint-Amour</td><td>Puiseaux</td><td>Donnemarie (Trias) geologic structure</td></tr>
<tr><td>Distance</td><td>About 65 km</td><td>About 75 km by boat (42 km as the crow flies)</td><td>About 360 km</td><td>About 290 km (flying)</td><td>a dozen km</td></tr>
<tr><td>Start date</td><td>2030</td><td>2030</td><td>2030</td><td>2039</td><td>2039</td><td>2039</td></tr>
<tr><td>End date</td><td>2050</td><td>2050</td><td>2039</td><td>2050</td><td>2050</td><td>2050</td></tr>
</table>

[9] Within the limit of 3 Mtpy approximately
[10] About 2 to 5 Mtpy depending on whether is selected the pipeline portion to be reused for CO2 transport

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Transport mode	Pipelines	Train	Ship	Existing oil pipeline	Existing gas pipelines	Pipeline
Total CO_2 transported*	23.7 Mt	5.7 Mt	13.9 Mt	16.4 Mt	16.4 Mt	16.4 Mt
CO_2 form	Gas	Liquid	Liquid	Gas	Gas	Gas
CAPEX	13.6 M€	10.8 M€	174.4 M€	-	0.6 M€[11]	3.6 M€
OPEX	5.2 M€	19.0 M€	129.9 M€	64.8 M€	34.6 M€	0.9 M€
Total costs (uncorrected-undiscounted) M€	18.8 M€	29.9 M€	304.3 M€	64.8 M€	35.2 M€	4.5 M€
€/ton CO_2	18.1	5.2	21.9	3.95	2.15	0.3
M€/km	1.6	0.5	4.1	0.15	0.1	0.5

* Total CO_2 transported corresponds to process-related core emissions + emissions linked to energy consumed to capture CO_2

6.2.2.4 CO_2 Utilization

The single site where CO_2 is used is in the one of ArcelorMittal steel plant in Fos-sur-Mer (refer to 6.2.1.4).

6.2.2.5 Storage considered in the clusters

With a capacity assessed at 13.9 Mt, the storage site in Les-Saintes-Marie-de-la-Mer is full in mid-2039. A second storage site (Donnemarie Trias) located near Puiseaux in Paris basin is used over the 2039-2050 period. This second storage site is large enough (68.9 Mt) to accept the CO_2 captured in the Rhône Valley over the entire projection period.

[11] Cost associated with the compression needed to pass from the operation pressure of the oil pipeline to that of gas pipelines

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6.2.2.6 KPIs of the scenario

The long-term main scenario for Rhône Valley covers the 2026-2050 period. **50.5 Mt of CO_2 is captured** over this period, **of which 29.4 Mt are stored and 21.1 are used** to produce ethanol. CO_2 captured in Rhône Valley represents about 10% of what is planned by the French National Low Carbon Strategy.

→ Extract of the French National Low Carbon Strategy [15]: "Carbon capture and storage technologies (CCS) are also used, albeit prudently, in the baseline scenario. In 2050, they will allow us to avoid around 6 Mt CO_2 /year in industry and to annually achieve around 10 Mt CO_2 of negative emissions with energy production installations using biomass (BECCS for bioenergy with carbon capture and storage)."

The cost of CCUS chain is 42 €/ton of CO_2 avoided (discounted), with CO_2 capture representing the biggest part of costs (62%), before storage (21%) and transport (17%). It is cost-effective if EU-ETS CO_2 price is 44 €/t based on the underlying economic assumptions described in chapter 2. Discounted CCUS costs are 1 225 M€.

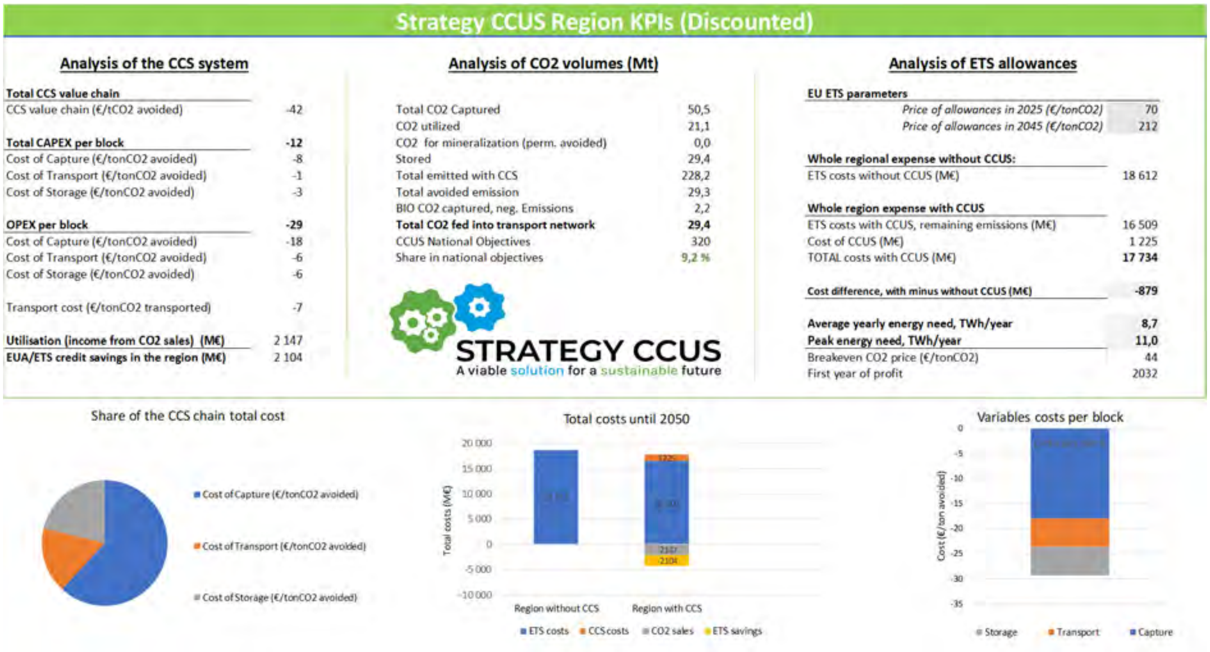

Figure 6-5 Overall cost analysis off the CCUS chain in Rhône Valley main long-term scenario

6.2.3 Rhone Valley Alternative Long-term scenario

6.2.3.1 Difference with the main scenario

The difference between Rhône Valley main and alternative scenarios is related to CO_2 storage:

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- In the main long-term scenario, CO_2 is first stored in Les-Saintes-Maries-de-la-Mer (Camargue) until mid-2039, then in a Triassic geologic structure in the Paris basin.
- In the alternative long-term scenario, **CO_2 is fully stored in this Triassic geologic structure in the Paris basin using 3 wells.**

The alternative long-term scenario for Rhône Valley is characterised by using a single CO_2 storage located in Paris basin from 2030 to 2050.

CO_2 is first carried by reusing an existing oil pipeline from Fos-sur-Mer to Saint-Amour. It is then carried by train from Saint-Amour to Auxy (passing by Montargis). Then, a new dozen km long CO_2 pipeline connects Auxy to Donnemarie (Trias) storage.

The reuse of gas pipelines is not here considered in view of the expected level of gas demand in 2030 which indicates that gas pipelines, overexploited in the northeast corner of France, will not be available to transport CO_2 at this time-horizon.

6.2.3.2 KPIs of the Alternative scenario

As for the main scenario, the alternative scenario covers the 2026-2050 period. There is no difference between Rhône Valley main and alternative scenarios in terms of equipped emitters (in neither level of capture nor efficiency and timescale). Thus, quantities of CO_2 to be captured, used, transported, and stored are the same.

The alternative scenario stands out from the main scenario because its main feature relies on the use of a single storage in Paris basin.

The cost of CCUS chain is 41 €/ton of CO_2 avoided (discounted), with CO_2 capture representing the biggest part of costs (62%), before storage (21%) and transport (17%). As for the Main long-term scenario, it is cost-effective if EU-ETS CO_2 price is 44 €/t. Discounted CCUS costs are 1 210 M€.

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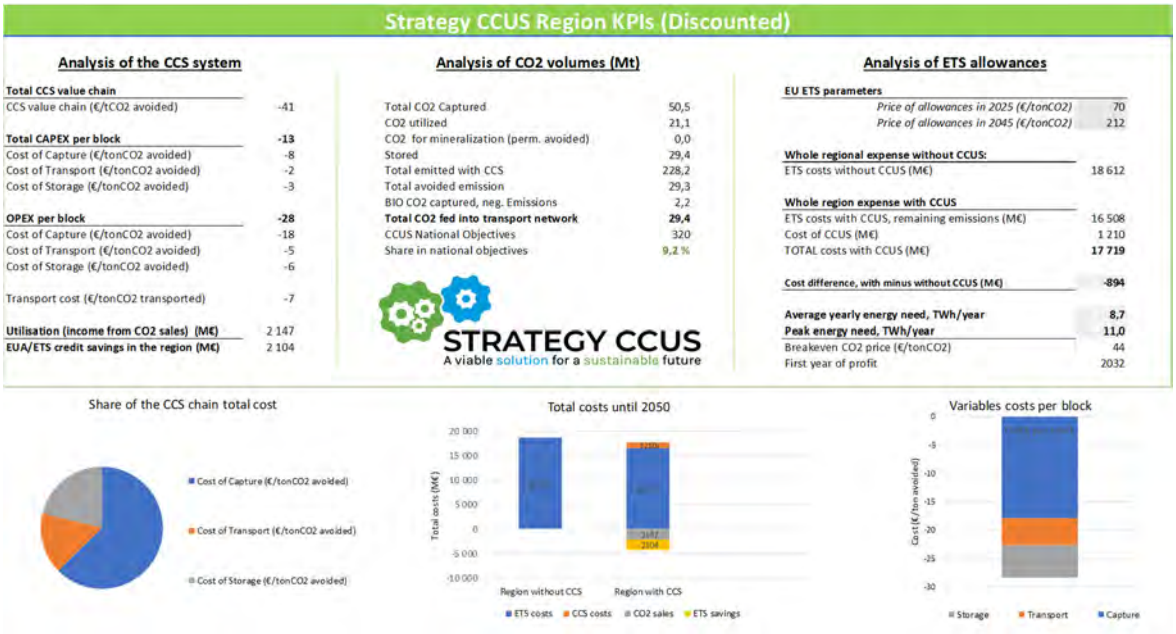

Figure 6-6 Overall cost analysis of the CCUS chain in Rhône Valley alternative long-term scenario

→ ArcelorMittal accelerates its decarbonisation in France with a 1 700 M€ investment program, supported by the Government [16]:ArcelorMittal recently changes its decarbonisation plan, particularly in its Fos-sur-Mer steel plant where 1.5 Mtpy of CO_2 is to be captured (2/3 to be stored & 1/3 to be used[12]) to the end of the period covered by the scenario. According to this new ArcelorMittal capture scheme - all other things being equal with regard to assumptions made in the alternative long-term scenario - the cost of CCUS chain is 1 940 M€ or 37 €/ton of CO_2 avoided (discounted), out of which 68% are attributed to capture, 18% to storage and 14% to transport.

6.2.4 Conclusion of the economic assessment of Rhone Valley scenarios

In any scenario considered for Rhône Valley, capture costs outweigh those of transport and storage as illustrated in Table 6-17 Comparative table of Rhône Valley scenarios KPIs.

Total CCS value chain is 41-42 €/t CO_2 avoided in the long-term scenarios in which the cost of CCUS[13] is assessed to be around €1.2 billion. These costs are specific to Rhône Valley scenarios where a CO_2 capture hub that concerns 6 emitters located within a fifty-kilometres radius is considered.

[12] It seems that no decision is made regarding CO_2 conversion pathway(s) to date. Methanol production is considered to perform the economic evaluation.
[13] CAPEX + OPEX

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Table 6-17 Comparative table of Rhône Valley scenarios KPIs

	Main scenario Short and medium-terms (2026-2039)	Main scenario Long-term (2026-2050)	Alternative scenario Long-term (2026-2050)
Total CCS value chain, €/t CO_2 avoided	36	42	41
Capture costs *(share)*	18 (49%)	26 (62%)	26 (63%)
Transport costs *(share)*	9 (26%)	7 (17%)	7 (16%)
Storage costs *(share)*	9 (26%)	9 (21%)	9 (21%)
Cost of CCUS (M€)	526	1225	1210
Breakeven CO_2 price	-	44	44

Finally, it must be pointed out that the eventuality of an offshore storage off Marseille is not here discussed (lack of information on subsurface geology characteristics that makes the economic evaluation impossible).

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7 Economic evaluation of Northern Croatia

7.1 Northern Croatia Main Scenario (short and medium-term)

7.1.1 Clusters emissions before CCUS

Industrial CO_2 emissions in Northern Croatia identified as part of WP2 of the STRATEGY CCUS project are 5.53 Mt in 2018. Two emitters are not included in any cluster, and the rest 10 emitters are grouped in two clusters considering their locations: Central and Eastern. Although the Eastern cluster accounts for around 15.5% of the overall CO_2 emissions in Northern Croatia, it was chosen for the Main Scenario due to the geographical distribution of its emitters. Although the earlier version of the scenario (WP5.2) was technically feasible, considering the needs for storage of each emitter new scenarios presented here are more likely to be realised.

Three industrial sites are considered for CO_2 capture in the Main scenario for short and medium-term. CO_2 emissions of these sites were 0.86 Mt in 2018. Given the CCUS roadmap hereafter described, 7.72 Mt of CO_2 would be captured in the short and medium-term (2025-2035) by equipping these 3 sites, which translates into 12.3 Mt of CO_2 when taking extra energy use increase into account.

7.1.2 Emitters considered for capture technology

Emitters considered for capture are presented in D5.2 [1]. There are around 90 kilometres (via road) between these sites.

Table 7-1 Industries with capture in North Croatia (Eastern Cluster) in the short and medium terms

Unit ID	E#01	E#02	E#03
Facility name	Našicecement d.d.	TE-TO OSIJEK	Viridas Biomass
Industry sector	Cement	Power	Power
2018 Reported emission (Mt/y)	0.65	0.11	0.10
CCU/CCS	CCU/CCS	CCU/CCS	CCS
Start Year	2025	2025	2030
End Year	2035	2035	2035
Efficiency	90%	70%	80%
CO2 Capture rate (%)	90%	70%	80%

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CO2 captured (Mt/y)	0.65	0.11	0.10
Total CO2 emitted if not captured (Mt)	6.39	0.85	0.49

7.1.3 Transport mode

All CO_2 transport is foreseen to be via pipelines as illustrated in Table 7-2. Most of the pipelines carry the captured CO_2 to hubs, and one pipeline carries the captured CO_2 directly to one storage unit.

Table 7-2 Transport mode in Northern Croatia main scenario in the short and medium-term

Transport mode	Pipelines						
From	E#01	E#02	E#03	H#01	SU#02	SU#03	H#02
To	H#01	SU#02	H#01	SU#03	H#01	H#02	SU#04
Distance (Km)	27	12	49	30	26	15	8
Total CO_2 transported (Mt)	10.62	1.16	0.55	12.33	1.16	11.25	11.25
CAPEX	7.5 M€	1.8 M€	8.8 M€	8.6 M€	4.8 M€	4.9 M€	1.3 M€
OPEX	4.5 M€	0.5 M€	4.3 M€	8.1 M€	1.2 M€	4.3 M€	0.2 M€
Total costs (uncorrected-undiscounted)	12.0 M€	2.3 M€	13.1 M€	16.7 M€	6.0 M€	9.2 M€	1.5 M€
€/ton CO_2	1.13	1.98	23.82	1.35	5.17	0.82	0.13
M€/km	0.44	0.19	0.27	0.56	0.23	0.61	0.19

7.1.4 CO2 Utilization

Part of the captured CO_2 from two emitters (Našicecement d.d. and TE-TO Osijek) will be used for EOR process in Beničanci oil field via H#01 in the period from 2025 to 2030.

Table 7-3 CO_2 utilization in Northern Croatia

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CO2 utilization	
Industry	Hydrocarbon production
Product	EOR
Quantities	0.324 Mt cumulative oil production
Total CO_2 used	1.076 Mt
EU ETS credit savings	728 M€

7.1.5 Storage considered in the clusters

The storage site considered for the short and medium-term main scenario is a depleted hydrocarbon field in Northern Croatia Bokšić. Its capacity is 13.6 Mt, and the injection would stop in 2035 without reaching the field's full capacity.

Table 7-4 Storage considered in the short, and medium terms main scenario for Northern Croatia

Storage	SU#04
Localisation	Northern Croatia, Bokšić & Onshore
Start date of storage	2025
End date of storage	2035
Total CO_2 stored	11.25 Mt
Cost of Storage	28 €/ton CO_2 avoided

7.1.6 KPIs of the scenario

The short and medium terms Main scenario for Northern Croatia cover the 2025-2035 period. This time window is considered because CO_2 injection is already planned for this period in the case of oil field and the other hydrocarbon (natural gas) field is at higher technological readiness level than for aquifers (injected after 2035 in long-term observation).

Over this period 12.3 Mt of CO_2 is captured, of which 1.1 Mt are used for enhanced oil recovery and 11.3 Mt are stored in a depleted hydrocarbon field.

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The cost of CCUS chain is 28 €/ton of CO_2 avoided (discounted), with CO_2 storage representing the biggest part of costs (56%), before capture (37%) and transport (7%). The breakeven CO_2 price of the scenario is of 33 €/tCO_2 avoided.

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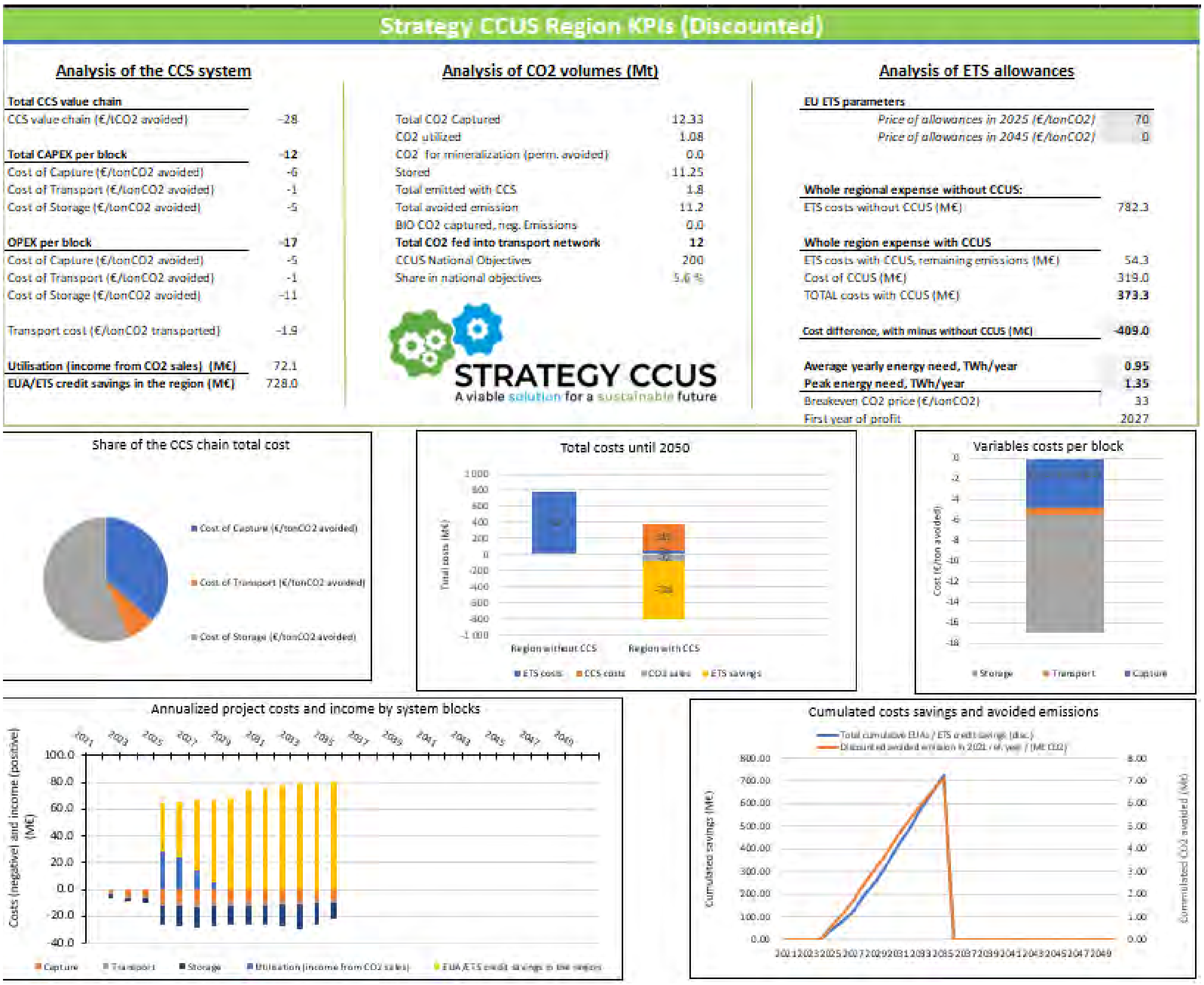
Figure 7-1 Overall cost analysis off the CCUS chain in Northern Croatia main scenario in the short, and medium-term



7.2 Northern Croatia Main Scenario (long-term)

The long-term scenario can be considered an extension of the short and medium-term one as in the period from 2025 to 2035 the same emitters, transport, utilization, and storage parameters are used. In the period from 2036 to 2050, the emitters remain the same, one pipeline is added, utilization enters its second phase (2035-2040), and that site is closed between the two EOR phases and converted into a storage in 2041. Additionally, in 2036 one aquifer is activated as storage site until the end of considered period.

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7.2.1 Clusters emissions before CCUS

Given the CCUS roadmap hereafter described, 18.81 Mt of CO_2 would be captured in the long-term (2025-2050) by equipping the same three emitters as in the short and medium-term. This translates to 29.8 Mt of CO_2 when taking extra energy use increase into account.

7.2.1.1 Emitters considered for capture technology

Unit ID	E#01	E#02	E#03
Facility name	Našicecement d.d.	TE-TO OSIJEK	Viridas Biomass
Industry sector	Cement	Power	Power
2018 Reported emission (Mt/y)	0.65	0.11	0.10
CCU/CCS	CCU/CCS	CCU/CCS	CCS
Start Year	2025	2025	2030
End Year	2050	2050	2050
Efficiency	90%	70%	80%
CO2 Capture rate (%)	90%	70%	80%
CO2 captured (Mt/y)	0.58	0.08	0.08
Total CO2 emitted if not captured (Mt)	15.1	2.0	1.8

7.2.1.2 Transport mode

The number of pipelines remains the same as in the short and medium-term Main scenario, but the transported quantities are not the same (the unit cost decreases).

Transport mode	**Pipelines**						
From	E#01	E#02	E#03	H#01	SU#02	SU#03	H#02
To	H#01	SU#02	H#01	SU#03	H#01	H#02	SU#04
Distance	27	12	49	30	26	15	8

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Total CO2 transported	25.10 Mt	17.38 Mt	1.93 Mt	28.19 Mt	1.16 Mt	27.05 Mt	11.25 Mt
CAPEX	7.5 M€	1.8 M€	8.8 M€	8.6 M€	4.8 M€	4.9 M€	1.3 M€
OPEX	4.5 M€	0.5 M€	4.3 M€	8.1 M€	1.2 M€	4.3 M€	0.2 M€
Total costs (uncorrected-undiscounted)	12.0 M€	2.3 M€	13.1 M€	16.7 M€	6.0 M€	9.2 M€	1.5 M€
€/tonCO2	**0.48**	**0.13**	**6.79**	**0.59**	**5.17**	**0.34**	**0.13**
M€/km	0.44	0.19	0.27	0.56	0.23	0.61	0.19

7.2.1.3 CO_2 Utilization

The CO_2 utilization is continued in the period from 2036 to 2040 in Beničanci oil field in terms of enhanced oil recovery but with emphasis on CO2 storage rather than increased production.

CO2 utilization	U#01
Industry	Hydrocarbon production
Product	EOR
Quantities	0.326 Mt cumulative oil production
Total CO2 used	1.137 Mt

7.2.2 Storage considered in the clusters

After the storage ends in Bokšić, CO_2 is injected in the Deep Saline Aquifer Osijek, and from 2041 it is also stored in Beničanci depleted oil field.

Storage	SU#04	SU#03	SU#02
Localisation	Northern Croatia, Bokšić & Onshore	Northern Croatia, Beničanci & Onshore	Deep Saline Aquifer

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Storage	SU#04	SU#03	SU#02
Start date of storage	2025	2041	2036
End date of storage	2035	2050	2050
Total CO2 stored	11.25 Mt	2.27 Mt	15.11 Mt
Cost of Storage	24 €/tonCO2 avoided	125 €/tonCO2 avoided	17 €/tonCO2 avoided

7.2.3 KPIs of the Main long-term scenario

The long-term main scenario for Northern Croatia covers the 2025-2050 period. It is assumed that after 2050 the whole infrastructure remains in place for further use.

29.8 Mt of CO_2 is captured over this period, of which 1.1 Mt are used for enhanced oil recovery and 27.1 Mt are stored in depleted hydrocarbon fields and one aquifer.

The cost of CCUS chain is 27 €/ton of CO_2 avoided (discounted), with CO_2 storage again representing the biggest part of costs (55%), before capture (40%) and transport (5%). It is cost-effective if EU-ETS CO_2 price is at least 30 €/t.

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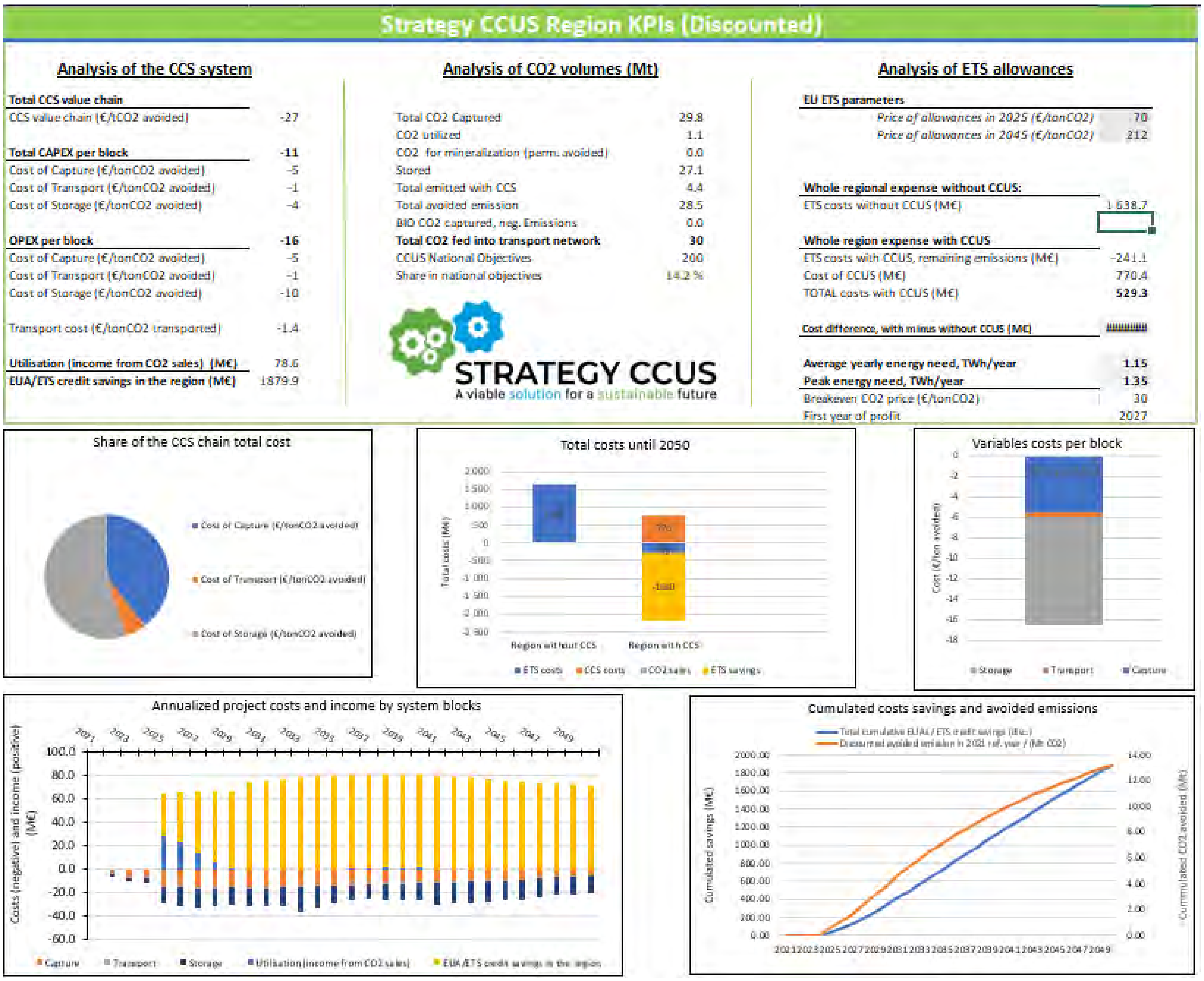

7.3 Northern Croatia Alternative scenario

7.3.1 Difference with the main

The biggest difference between the main and the alternative scenario is related to CO_2 storage:

- In the main long-term scenario, the CO_2 is used for EOR in the Beničanci oil field in two phases, then turned into a storage site. Furthermore, CO_2 is stored in Bokšić depleted oil field and in DSA Osijek.
- In the alternative long-term scenario, the CO_2 is additionally stored in DSA Drava.

The alternative long-term scenario for Northern Croatia is characterised by using an additional CO_2 storage site from 2036 to 2050.

CO_2 is still transported via pipelines, and one additional pipeline is used in the alternative scenario.

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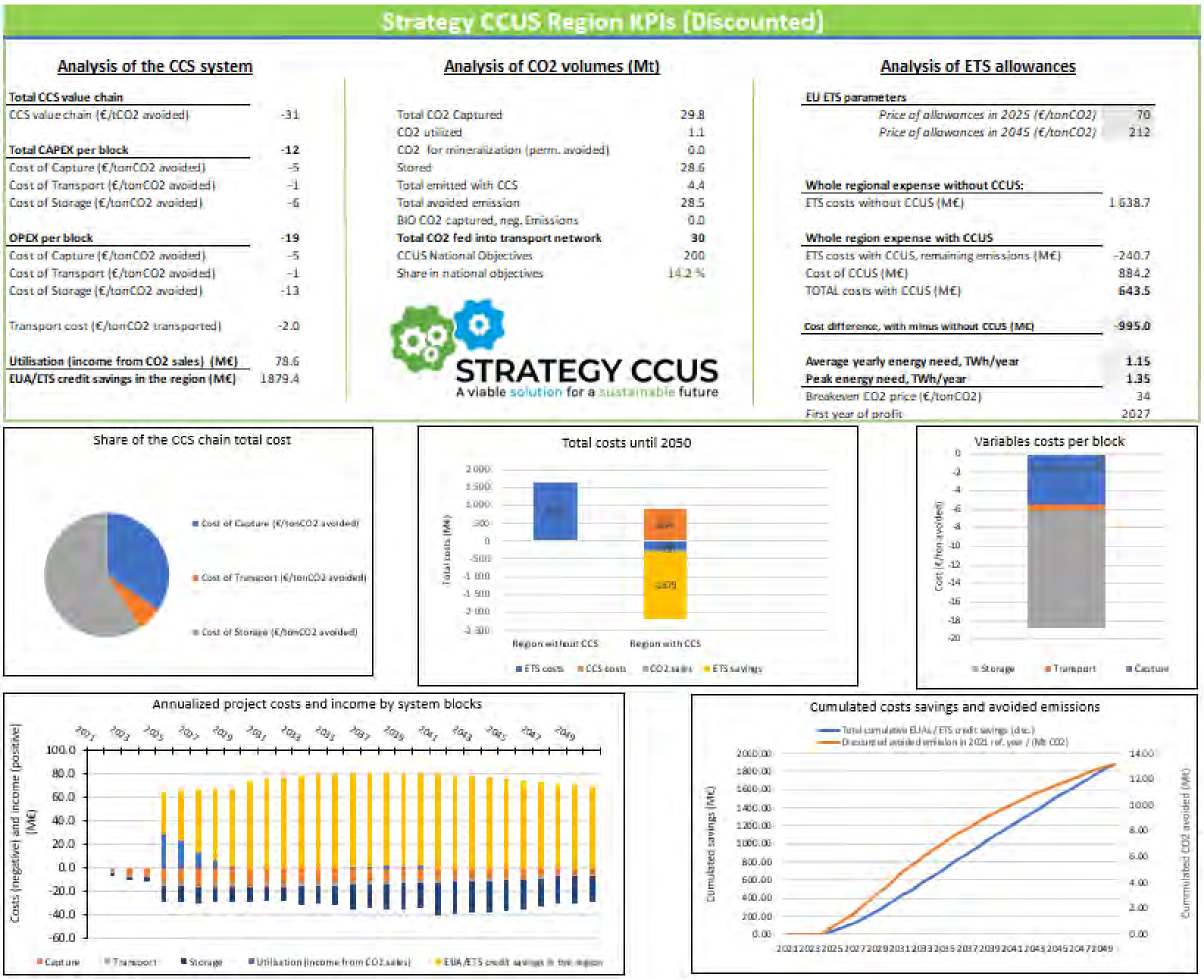
7.3.2 KPIs of the Alternative scenario

As for the main scenario, the Northern Croatia main and alternative scenarios in terms of equipped emitters (in neither level of capture nor efficiency and timescale). Thus, quantities of CO_2 to be captured, used, transported, and stored are the same.

The cost of CCUS chain is 31 €/ton of CO_2 avoided (discounted), with CO_2 storage representing the biggest part of costs (59%), before capture (34%) and transport (7%). The breakeven CO_2 price of the scenario is of 34 €/t CO_2 avoided.

CCUS chain value in the alternative scenario is around 15% higher than in the main scenario which can be explained by putting the additional storage site into operation.

Figure 7-2 Overall cost analysis of the CCUS chain in Northern Croatia alternative scenario for the short, medium, and long-term



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7.4 Conclusion of the economic assessment Northern Croatia scenarios

In any scenario related to Northern Croatia, costs of storage outweigh those of transport and capture as illustrated in Table 7-5.

Total costs of CCS value chain range from 28 €/t CO_2 to 27 €/t CO_2 avoided in the main scenario (short and medium-term vs. long-term). This is largely due to the change in investment to return ratio spanning over the lifetime of the project.

Total costs of CCS value chain are a bit higher in the alternative scenario than in the main one because of larger investments due to injection into additional aquifer.

Table 7-5 Comparative table of Northern Croatia scenarios KPIs

€/tCO2 avoided	Main scenario Long-term	Alternative scenario Long-term
Total costs of CCS value chain	**27**	**31**
Storage costs *(share)*	15 *(55%)*	18 *(59%)*
Capture costs *(share)*	11 *(40%)*	11 *(34%)*
Transport costs *(share)*	1 *(5%)*	2 *(7%)*
Breakeven CO2 price	**30**	**34**

Compared to long-term scenarios implemented in the 7 other regions the project covers, the case of Northern Croatia is in the middle range, both in terms of quantity of captured CO_2 and costs.

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8 Romania: economic evaluation of the Galati basin

8.1 Galati Basin Main Scenario (short- and medium-term)

The short- and medium – term scenario for Galati region starts in 2025 and end in 2029 (last year). Within this scenario, carbon capture, utilization and storage are implemented only in the Galati sub-cluster. Tulcea sub-cluster begins operation from 2030.

8.1.1 Cluster(s)r emissions before CCUS

Within Galati sub-cluster, at the moment, only Liberty Steel Galati, the largest integrated steel plant in Romania, is in operation. In 2020, Liberty Steel Galati has reported emissions of approximately 3.8 Mt CO_2, according to the data published by the National Agency for Environmental Protection. This amount represents more than 93% of total emissions per region which were reported to be 4.17 Mt in 2020.

8.1.2 Emitters considered for capture technology

On the short and medium – term was taking into consideration deployment of CO_2 capture at two facilities, Liberty Steel Galați (E#1) and a new gas-fired power plant, named hereafter Romgaz CCGT (E#2). This latest emitter is planned to produce electricity and fuel the processes from the steel production. The emitters and the amounts of CO_2 to be captured on this scenario are presented in Table 7-6. For Liberty Steel Galați, only 25% of emissions from 2020 will be captured due to their increase in efficiency and changing of fuel. The economic results for the capture part are presented in Table 7-6.

Table 7-6. Emitters considered for capture technology in the short-medium term scenario

Industries with capture per hub		
	Liberty Steel Galati	Romgaz CCGT
Sector	Iron&steel	energy
Capacity (MW)	-	482
Total CO_2 captured (from fossil fuel) – Mt CO_2	5.496	1.235
Total costs (M€ undiscounted)	142	566.3
Total Capex/Opex (€/t CO_2 avoided) M€ undiscounted	25.83	458.54

8.1.3 Transport mode

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For the short- and medium-term scenario, only onshore pipeline transport (see the economic results in Table 7-7) will be operated, connecting emitters E#01 and E#02 to an onshore hub which allows distribution of captured CO_2 to storage sites and a utilization unit (EOR).

Table 7-7. Transport modes in the short-medium term scenario

Transport mode	
	Pipeline
From	Galati industrial platform
To	Onshore storage sites and utilization site
Total CO_2 transported	6.73
Total costs M€ discounted	12.1
€/t CO_2 avoided discounted	1.9

8.1.4 CO_2 Utilization

In this scenario, before 2030, only one CO_2-EOR site will be operated, namely Oprișenești field (U#01). CO_2-EOR is the only utilization for captured CO_2.

Table 7-8. Utilization considered for the short-medium term scenario

CO_2 utilization	
	From E#01 and E#02
To industry	CO_2-EOR, Oprișenești field
Total CO_2 used (Mt CO2)	0.25
CO2 used/t	1.86
Total revenues from CO_2 used (M€ discounted)	32.3

8.1.5 Storage considered in the clusters

Before 2030, only two onshore storage sites (depleted onshore gas fields) will be opened, Ghergheasa (SU#02) and Balta Albă (SU#04). The economic results of the storage part are presented in Table 7-9.

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Table 7-9. Storage considered in the short-medium term scenario

Storage	SU#02	SU#04
Name	Ghergheasa	Balta Albă
Localisation	onshore	onshore
Start date of storage	2028	2025
Total CO2 stored	1.04	5.,44
Total cost, undiscounted (M€)	45.61	67.26
Cost per ton CO_2 (€/ton) undiscounted	43.98	12.35

8.1.6 KPIs of the scenario

Total cost of the CCUS chain in terms of €/tCO_2 avoided is 43, 021.6 € for CAPEX and 21.8 € for OPEX, as it can be seen from the KPIs presented below. The largest share of the costs along the CCS chain is represented by the costs of capture, as it can be seen from Figure 7-3.

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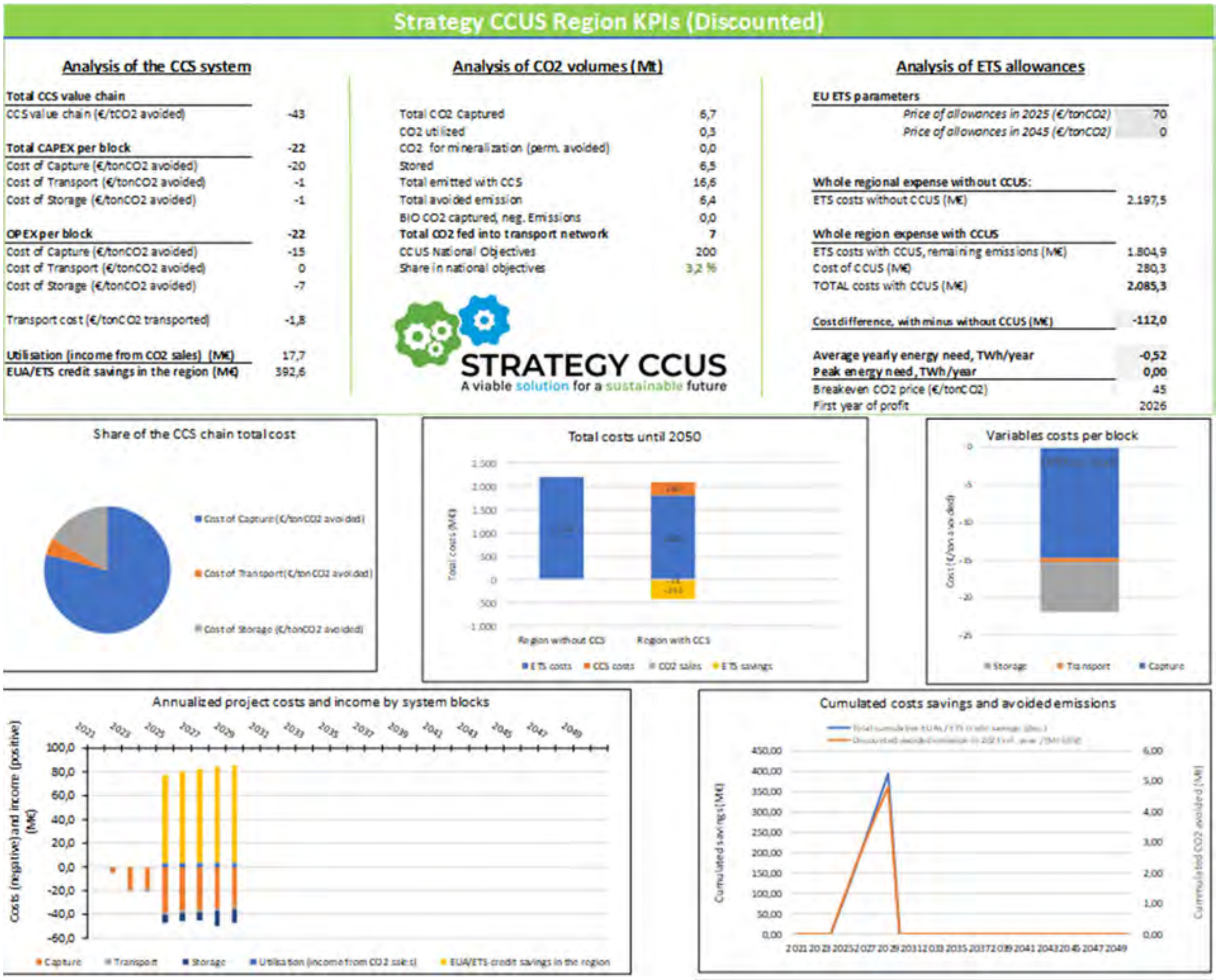

Figure 7-3. KPI's for the short-medium term scenario for Galati region

8.2 Galati Basin Main Long-term scenario 2050

8.2.1 Cluster(s)r emissions before CCUS

The emissions in Galați region can be grouped into two sub-clusters, Galați and Tulcea. In Galați sub-cluster, only Liberty Steel is operating, as mentioned before. In Tulcea sub-cluster, the only emitters currently operating are Sectia CET; Instalatia CALCINAREA Al(OH)- named hereafter Alum (E#03), a non-iron production facility, and "S.C. Energoterm S.A. Tulcea - C.A.F. Nr. 1" – named hereafter Energoterm (E#04), a small heat producer. The level of emissions was presented in Deliverable D5.2 [1]. the total emissions without CCUS would be 30 Mt CO_2 for Galați sub-cluster and 4.24 Mt for Tulcea sub-cluster.

8.2.2 Emitters considered for capture technology

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On the long term, for capture technology, 2 emitters per sub-cluster were considered. For Galați sub-clustered we considered Galați Liberty Steel (E#01) with a capture rate of 0.25 of total emissions from 2020 and Romgaz CCGT (E#02) with a capture rate from 0.9 from a total estimated emission of 0.2 Mt of CO_2 per year. For Tulcea sub-cluster, we have also 2 emitters, Alum (E#03) with a capture rate of 0.9 from 0.21 Mt (reference year 2020) and Energoterm (E#04) with a capture rate of 0.9 from a total of 0.01 Mt (reference year 2020). Emitters considered for capture technology within the main long-term scenario and their economic indicators are presented in Table 7-10.

Table 7-10. Industries with capture in the main long-term scenario for Galați region

Industries with capture per hub				
Facility name	Liberty Steel Galati	Romgaz CCGT	Alum	Energoterm
Sector	iron&steel	Power	Non iron	Power
Power gross capacity (MW)		67,56	71,63	4,07
Start year	2025	2025	2030	2030
End year	2050	2050	2050	2050
Total CO_2 captured (from fossil fuel) – MtCO2	28.58	6.42	5.498	0.31
Total CO_2 captured (from Biomass) – Mt CO_2	-	-	-	-
Total costs (M€) undiscounted	282.3	988.33	181.4	154.5
Total Capex/Opex (€/t CO_2 avoided) M€ undiscounted	9.88	153.95	32.99	498.39

8.2.3 Transport mode

Within the Galati sub-cluster, the transport mode is made only by onshore pipelines. For Tulcea sub-cluster, the transport is made by onshore pipelines to connect the emitters with the fluvial hub. From this hub, located in the Tulcea harbour, the captured CO_2 is transported along the Danube by ships to the Sulina hub that connects to the storage site in the Black Sea. The economic indicators for the main transport modes are presented in Table 7-11.

Table 7-11. Transport mode for the main long-term scenario. Galați region

Transport mode

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	Pipelines Galati sub-cluster	Pipelines Tulcea sub-cluster	Ships Tulcea sub-cluster
From	Emitters E#01 and E#02	Emitters E#03 and E#04	From Tulcea harbour and Sulina harbour
To	Onshore hub near Galati and storage and utilizations sites	Tulcea harbour (hub)	Storage site in the Black Sea
CO_2 transport capacity (Mt)	122.74	11.31	11.62
Total costs undiscounted (M€)	74.9	2.4	272.4
Total energy used (GWh)	18.8	0	247.9
Total cost (€/ton CO_2 avoided)	0.61	0.21	23.45

8.2.4 CO_2 Utilization

The only utilization option in the main long-term scenario is EOR, implemented at three oil (Oprișenești, Bordei Verde Est and Lișcoteanca) fields, using part of the CO_2 emitted from Liberty Steel (E#01) and Romgaz CCGT (E#02). The implementation of EOR in the three fields have different start and end dates as described in deliverable D5.2 [1]. The result of the economic analysis for the utilization part is presented in Table 7-12.

Table 7-12. Result of the economic assessment of the utilization part for the long- term scenario

CO_2 utilization	
From industry	E#01 and E#02
To industry	EOR
Total CO_2 used	5,8
CO_2 used (t) per ton of oil	2,97
Total revenues from CO_2 used (M€)	877.5

8.2.5 Storage considered in the clusters

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For Galați sub-cluster, only onshore storage is chosen in depleted gas fields, SU#04 (Balta Albă), SU#02 (Ghergheasa), SU#01 (Roșioru) and SU#03 (Bobocu). The storage will start with Balta Albă (SU#04) in 2025 and Ghergheasa (SU#02) in 2028. The other two fields are planned to begin operations starting with 2031 (Rosioru – SU#01) and 2035 (Bobocu – SU#03).

The only storage solution considered in this scenario for Tulcea sub-cluster is an offshore deep saline aquifer, SU#05 (Venus).

The economic indicators for storage considered in the long-term scenario are presented in Table 7-13.

Table 7-13. Storage considered in the main long-term scenario for Galați region

Storage	SU#1	SU#2	SU#3	SU#4	SU#5
Name of the unit	Roșioru	Ghergheasa	Bobocu	Balta Albă	Venus
Localisation	Onshore	Onshore	Onshore	Onshore	Offshore
Start date of storage	2031	2028	2035	2025	2030
End date of storage	2045	2050	2050	2032	2050
Total (net) CO_2 stored (Mt)	8,08	7,71	7,59	6,72	5,78
Total cost, undiscounted (M€)	137.1	191.9	124.2	87	355.2
Cost per ton CO_2 (€/ton)	19.45	23.73	17.28	12.75	42.82

8.2.6 KPIs of the scenario

The KPI's for the entire long-term scenario are presented in Figure 7-4. The total cost of the chain is 42 € /ton of CO_2 avoided, 15 € for CAPEX and 27 € for OPEX. The largest share of the costs is for capture. The breakeven CO_2 price of the scenario is of 43 €/t CO_2 avoided.

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

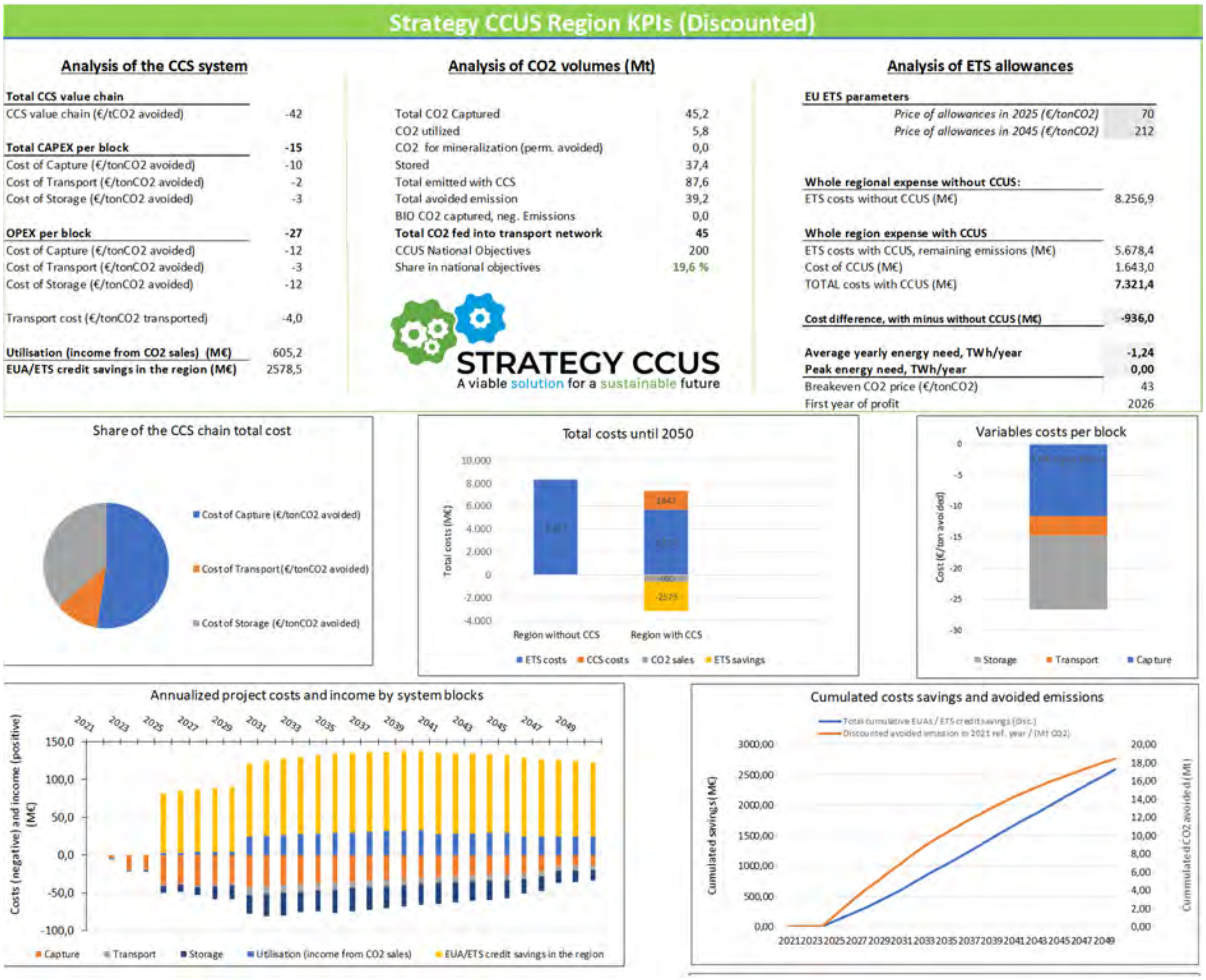

Figure 7-4. KPI's for the long- term scenario for Galati region

8.3 Galati Basin Alternative(s) scenario

8.3.1 Difference with the main

The alternative scenario is focused only on Galati sub-cluster, Tulcea sub-cluster is not included. The start date of the scenario is 2030, when all the capture units, storage and utilization units are becoming operational.

The capture is implemented at two facilities, Liberty Steel (E#01) and Romgaz CCGT (E#02). The transport is made only through onshore pipelines. Storage is considered at the 4 depleted gas fields included in the main long-term scenario and utilization is EOR implemented at the three oil fields mentioned before.

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8.3.2 KPIs of the Alternative scenario

The KPI's for the alternative scenario are presented in Figure 7-5. The total cost of the CCS is 44 € per ton of CO_2 avoided, 16 € for CAPEX and 28 € for OPEX. The largest share of the cost is represented also by capture, followed by storage and transport. The breakeven CO_2 price of the scenario is of 46 €/t CO_2 avoided.

CCUS chain value in the alternative scenario is slightly higher than in the main scenario, which can be explained by reducing the number of emitters from the cluster and therefore the quantity of CO_2 to be captured, transported and stored and also by reducing the duration of the project with 5 years. The difference is only 2 €/t CO_2 avoided.

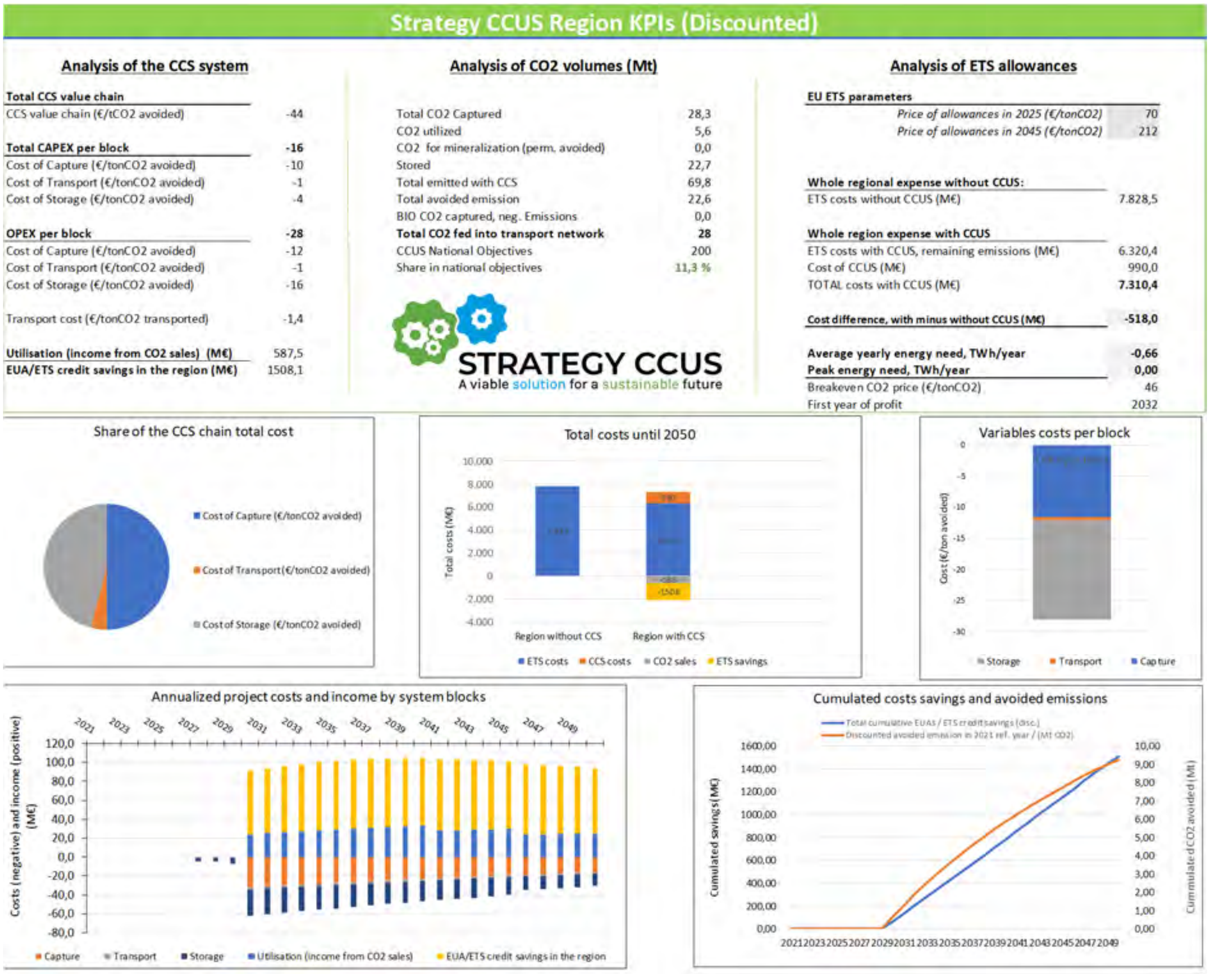

Figure 7-5. KPI's for the alternative scenario for Galati region

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8.4 Conclusion of the economic assessment of Galati scenarios

The costs of CCS value chain resulting from the application of the tool are clearly underestimated. This is due to the fact that the entire evaluation is based on different assumptions, literature and public data. In order to make a proper evaluation, specific, accurate data must be used, real and updated data from emitters and field data for the proposed storage sites. Unfortunately, these specific data could not be obtained for this project, but a first evaluation was realized and presented to the stakeholders.

There are still many uncertainties related to the proposed scenarios. One of the main uncertainties is represented by the plans of becoming carbon neutral of Liberty Steel Galati, the most important emitter of the region. Although the emitter does not seem to have a particular interest for CCS at present, it is clear that they will not reach carbon neutrality without implementing CCUS. This was underlined also during the regional stakeholder committees. The quantity of CO_2 that should be captured and stored is 25% from the emissions from 2020, as suggested by Liberty Steel representatives.

Another major uncertainty is represented by the construction of a new gas-fired power plant, the joint venture of Romgaz and Liberty Steel, announced in 2020. No details or updates have been disclosed in the past year and the proximity and implications of the war in Ukraine make it hard to predict.

The results of the evaluation of the main and alternative scenario are very similar, but there are differences in terms of the number of emitters, quantity of CO_2 to be captured and stored (45.2 t in the main scenario and 28.3 t in the alternative scenario), number of storages and the period of CCUS implementation (25 years in the main scenario and 20 years in the alternative scenario). Taking all this into consideration, the results show that the main investments are needed for Galati sub-cluster and implementation of CCUS in the Tulcea sub-cluster does not represent a significant effort for the region. It is essential to start CCUS with Liberty Steel.

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

9 Greece: economic evaluation of the Western Macedonian area

9.1 Western Macedonian Main Scenario (short- and medium-term)

9.1.1 Cluster(s) emissions before CCUS

At the current stage, there are two operational power plants in Western Macedonia, Agios Dimitrios and Meliti which are based on lignite extraction that emit CO_2.

Figure 9-1 shows the power plants location, whereas Table 9-1 presents information regarding the industrial plants in Western Macedonia and their annual CO_2 emissions for the 2017 year.

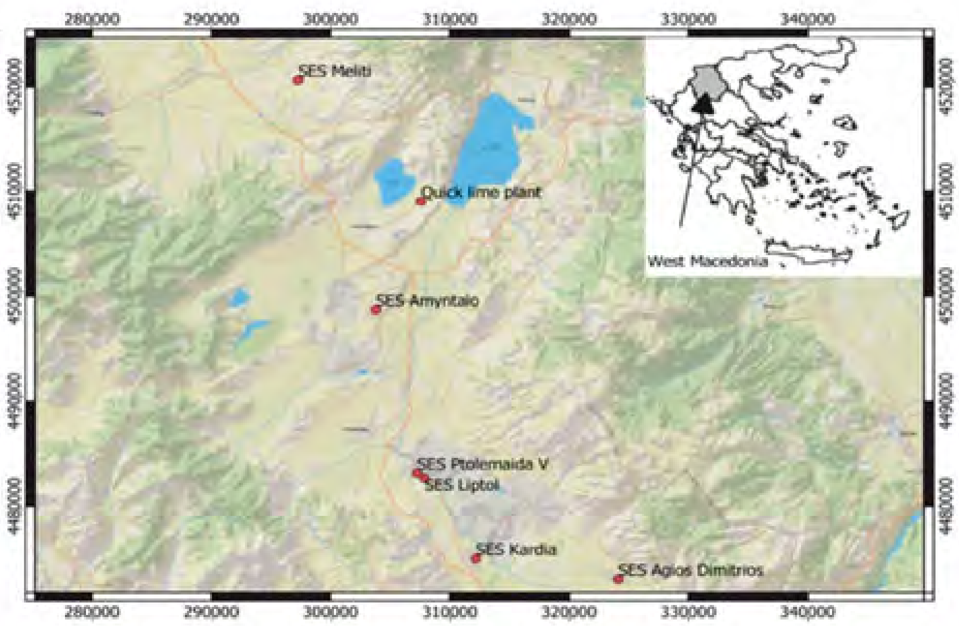

Figure 9-1 Locations of power and lime plants in Western Macedonia

Table 9-1: Industrial plants in Western Macedonia and annual CO_2 emissions up to year 2017.

Facility Name	Sector	City	Emissions (tCO_2/y)	Main Fuel
Agios Dimitrios	**Power 1587 MW**	**Kozani**	**8,940,000**	**Lignite**
Amyntaio	Power 600 MW	Amyntaio	2,760,000	Lignite
Kardia	Power 1200 MW	Ptolemaida	6,400,000	Lignite
Meliti	**Power 330 MW**	**Florina**	**2,270,000**	**Lignite**
Ptolemaida	Power 620 MW	Ptolemaida	2540,000	Lignite
Liptol	Power 43 MW	Ptolemaida	118,000	Lignite
Ptolemaida V	**Power 660 MW**	**Ptolemaida**	**4,500,000 (estimated)**	**Lignite**
Amyntaio	Quicklime	Amyntaio	40,150 (estimated)	No Data

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9.1.2 Emitters considered for capture technology

Based on the new Greek National Energy and Climate Plan, all operating power plants will be retired by 2023. **The only remaining operational lignite power plant will be the Ptolemaida V from 2023**. Ptolemaida V is in North-Western Greece, at the old, exhausted "Komanos" coal mine. TERNA S.A. being the EPC contractor is responsible for putting into operation of Ptolemaida V, fired with pulverised lignite and capable of generating 660 MW_{el} gross power and delivering thermal power 140 MW_{th} for district heating. The CO_2 emissions available for CO_2 capture from Ptolemaida V power-plant, estimated at 4.5 Mt/y for 30 years. The plant is designated as a CCS-ready facility.

Some key advantages of this new power plant are: decrease of lignite consumption by 40%, decrease of greenhouse gas emissions by 40%, decrease of pollutant emissions by 60%, decrease of particles emissions by 90%.

9.1.3 Transport mode

For the Greek medium-term Main scenario, only one emitter, Ptolemaida V, was taken under consideration. The currently under-construction unit is destined to be the only operating power-plant from 2023 and onwards in the Western Macedonia region.

The medium-term Main scenario for the Western Macedonia region starts from 2030 and ends in 2040. The flow rate of CO_2 for each transportation route, by pipeline or train, is stable and presented in Table 9-2 .

Table 9-2: The flow rate for all transportations during the medium-term scenario.

Segment ID, flow rate (Mt/y)	From 2030 to 2040
P#01	4
T#01	0.5
P#02	2
P#03	2

The basic design parameters of all three pipelines in this scenario has the same values. However, there are differences in the distance, elevation profiles and terrain factors taken under consideration in each route.

The train transportation of CO_2, chosen in the case of Air Liquid Hellas in Florina, allows minimizing the total transportation costs of the scenario. The wagon's capacity of the train was calculated at 240tn. Thus, a locomotive with three wagons is required, making 679 (maximum) trips per year to satisfy the needs of the first utilization site.

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KPIs and basic design parameters for the first pipeline from E#01 to SU#01 and train transportation from E#01 to U#001 are presented in the following tables (Table 9-3 to Table 9-6). The other pipelines connections are designed, accordingly.

Table 9-3: Basic design parameters of pipeline from emitter to storage unit

Pipeline basic design parameters	Units	INPUT
Upstream / inlet / desired outlet pressure	bar	110 / 140 / 110
Pipeline length	m	66,619
Elevation difference	m	-249
Start year	y	2027
Total number of years	y	14

Table 9-4 KPIs of pipeline from emitter to storage unit.

Key KPIs:		
NPV (costs) in year 2021 (undiscounted / discounted)	€M	37.23 / 18.56
Total CO2 transported	Mt	20.37
Total CO2 emitted	Mt	0.01
CO2 transport costs per ton (undiscounted / discounted)	€/t	1.83 / 0.91

Table 9-5: Basic design parameters of train transport from emitter to first utilization site.

Train Basic design parameters	Units	INPUT
Upstream / transport pressure	bar	90 / 50
Upstream / transport temperature	°C	25 / -10
Wagon capacity	t	240
Distance	m	67,480
Start transport	y	2030

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Table 9-6: Key KPIs for the train transportation

Key KPIs:		
NPV (costs) in year 2021 (undiscounted / discounted)	€M	32.61 / 19.09
Total CO_2 transported	Mt	3.66
Total CO_2 emitted	Mt	0.05
CO_2 transport costs per ton (undiscounted / discounted)	€/t	9.03 / 5.29

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9.1.4 CO_2 Utilization

Table 9-7 presents the utilization results for the currently medium-term Main scenario and products KPIs. The maximum CO_2 will be utilised in the medium-term Main scenario from 2036 to 2040.

Table 9-7: Products KPI

Products KPI	Mt of products from CO2 utilization(total)	CO_2 used/ton
CO2 pure (food, …)	1.46	2.5
e-fuels	6.44	1.7

9.1.5 Storage considered in the clusters

In Figure 9-2, the storage scenario for Pentalofos closed storage unit is presented. CO_2 injection will be at the maximum level for the first three years (2030-2033), and following these years, the amount of injected CO_2 will gradually begin to be reduced. Moreover, Figure 9-3 appears the number of wells essential for medium-term scenario implementation.

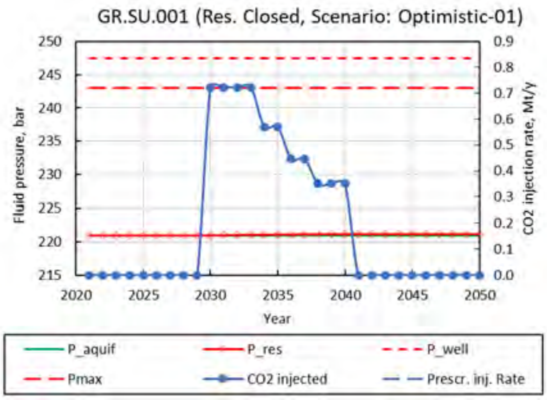

Figure 9-2: Storage medium-term scenario for the West Macedonia area.

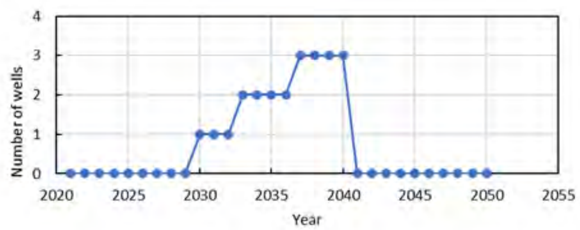

Figure 9-3 Number of required wells in the medium-term scenario.

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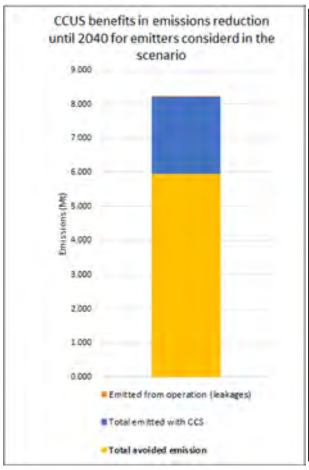
Table 9-8 presents the KPIs for Pentalofos storage unit for medium-term Main scenario (2030-2040). In particular, the total amount of net CO_2 which will be stored is 5.98 Mton, while the total emitted one is 0.03 Mton. Moreover, total undiscounted costs will be 25.6 million euros, whereas the undiscounted CO_2 cost per ton will be up to 4.3 euro per ton.

Table 9-8: KPIs for Pentalofos storage unit in Greek medium-term scenario.

Key KPIs for GR.SU.001, Scenario ID: Optimistic-01	Closed	Unit
NPC in year 2021 (undiscounted / discounted)	-25.6 / -8.8	M€
Total CO_2 stored	5.98	Mton
Total CO_2 emitted	0.03	Mton
CO_2 costs per ton (undiscounted / discounted)	-4.3 / -1.5	€/ton
First year / Last year of full injection	2030 / 2040	yr

Emission benefits from CCUS technology application in West Macedonia area are presented in Figure 9-4 and in Figure 9-5. The environmental CCUS benefits are clear enough in which the CO_2 flows - in this medium-term Main scenario - are depicted in detail.



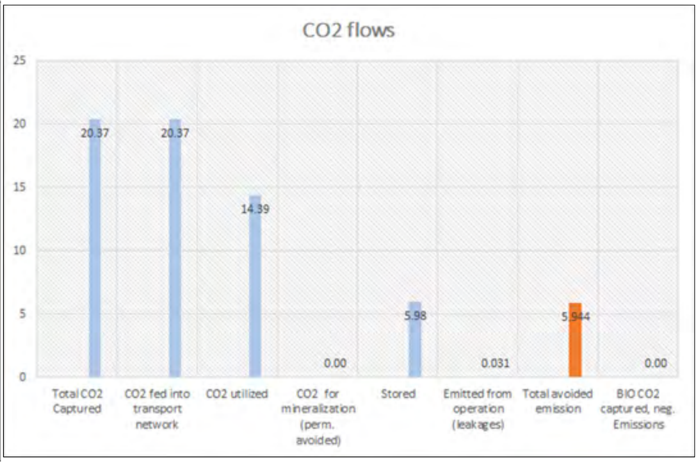


Figure 9-4: Regional emissions reduction until 2040 and

Figure 9-5: CO_2 flows in the medium-term scenario for the West Macedonia area

CCUS West Macedonia KPIs of medium-term scenario are presented in **Erreur ! Source du renvoi introuvable.**. This figure includes the analysis of CCS system, of CO_2 volumes and of ETS allowances.

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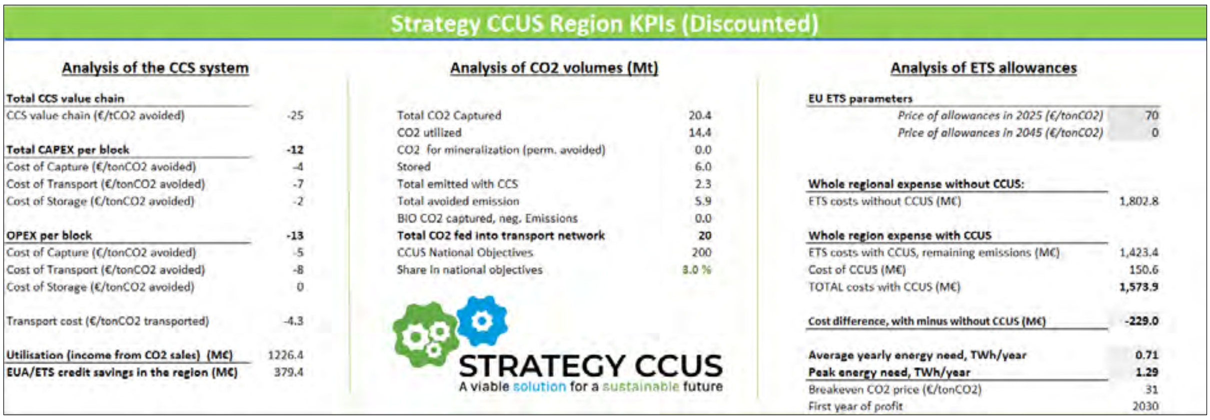
In particular, 20Mt of CO_2 are captured in the medium-term scenario, 20 Mt are transported, 14 Mt are utilised and 6 Mt are stored. The avoided emission is 6 Mt CO_2.


Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-25
Total CAPEX per block	**-12**
Cost of Capture (€/tonCO2 avoided)	-4
Cost of Transport (€/tonCO2 avoided)	-7
Cost of Storage (€/tonCO2 avoided)	-2
OPEX per block	**-13**
Cost of Capture (€/tonCO2 avoided)	-5
Cost of Transport (€/tonCO2 avoided)	-8
Cost of Storage (€/tonCO2 avoided)	0
Transport cost (€/tonCO2 transported)	-4.3
Utilisation (income from CO2 sales) (M€)	1226.4
EUA/ETS credit savings in the region (M€)	379.4

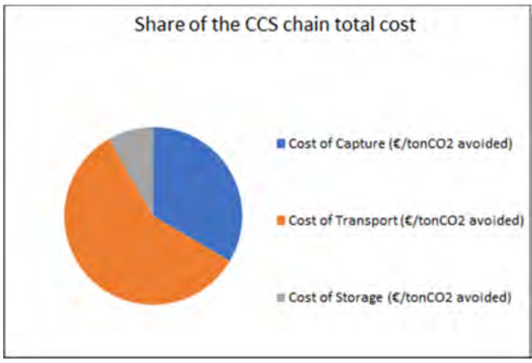
Analysis of CO2 volumes (Mt)

Total CO2 Captured	20.4
CO2 utilized	14.4
CO2 for mineralization (perm. avoided)	0.0
Stored	6.0
Total emitted with CCS	2.3
Total avoided emission	5.9
BIO CO2 captured, neg. Emissions	0.0
Total CO2 fed into transport network	**20**
CCUS National Objectives	200
Share in national objectives	8.0 %

Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	0
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	1,802.8
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	1,423.4
Cost of CCUS (M€)	150.6
TOTAL costs with CCUS (M€)	**1,573.9**
Cost difference, with minus without CCUS (M€)	**-229.0**
Average yearly energy need, TWh/year	**0.71**
Peak energy need, TWh/year	**1.29**
Breakeven CO2 price (€/tonCO2)	31
First year of profit	2030

Figure 9-6 : Region KPIs of medium-term scenario



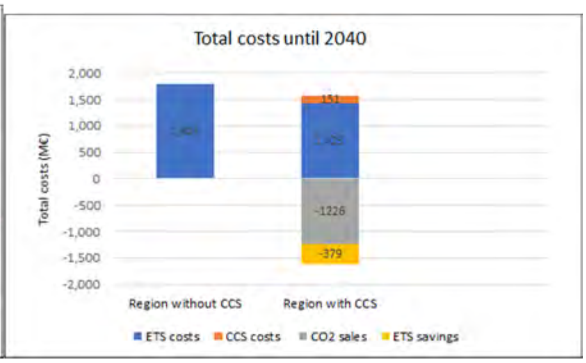


Figure 9-7: Share of CCS total cost, and Figure 9-8 : Total regional costs until 2040.

In the CCS chain total cost, transport has the largest share while storage the smallest one (Figure 9-7). Moreover, CO_2 sales and ETS savings generate regional revenues and reduce significantly total costs (and Figure 9-8).

The avoided CO_2 emissions from CCUS technology application in West Macedonia are about 6 Mt. **Erreur ! Source du renvoi introuvable.** shows the undiscounted Capex for West Macedonia which is a) 46.7 million euros in the capture stage, b) 78.1 million euros in the transport stage, c) 21.2 million euros in storage procedure.

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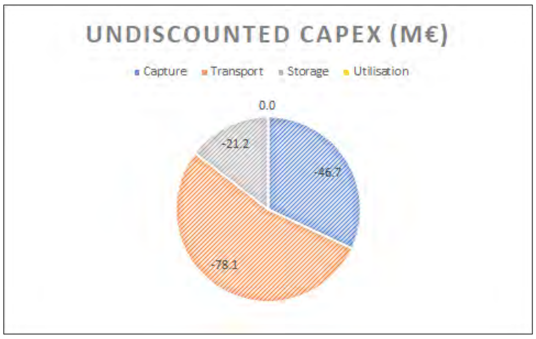

Figure 9-9: Undiscounted Capex for Greek medium-term Main scenario.

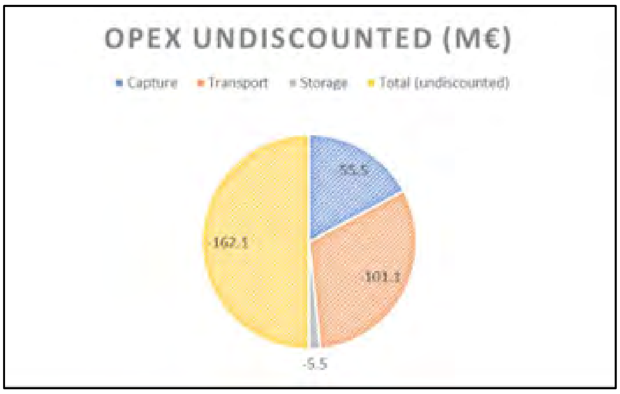

Figure 9-10: Undiscounted Opex for Greek medium-term scenario

The undiscounted Opex for the medium-term Main scenario is 162 million euros.

The fraction CAPEX (euro) per ton of CO_2 avoided is larger in the transport procedure (Figure 9-11).

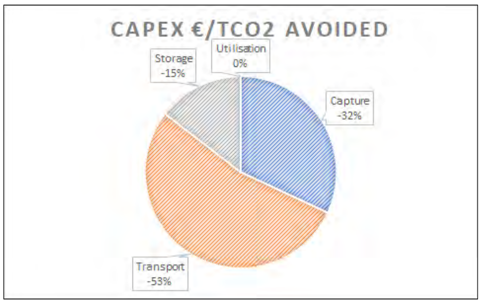

Figure 9-11: CAPEX per avoided CO_2 for Greek medium-term Main scenario.

The regional revenues from CO_2 utilization stage are unambiguous.

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Figure 9-12 shows the project costs and incomes for the West Macedonia region per year to implement a medium-term scenario. From 2027 to 2030, most costs will be for the transport procedure, followed by the storage stage. From 2030, the first year of the medium-term Main scenario, West Macedonia Region will start to have incomes from CO_2 sales and, also expenses avoided from EUA savings. Thus, during the medium-term scenario, the regional revenues are much higher than the costs. This means that the mid-term developed scenario is advantageous and profitable for the West Macedonia area both economically and environmentally.

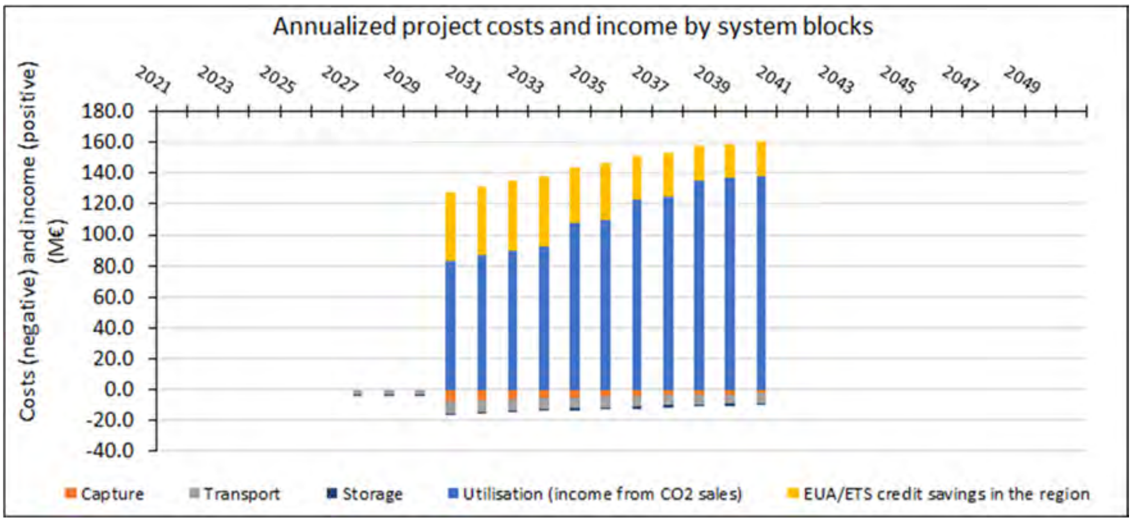

Figure 9-12: Regional costs and incomes for West Macedonia region in medium-term scenario.

9.2 Western Macedonian Main Long-term scenario 2050

9.2.1 Cluster(s)r emissions before CCUS

Same as the short-medium-term Main scenario. The long-term scenario is an extension of the short-medium one.

9.2.2 Emitters considered for capture technology

Same as the short-medium-term scenario. The long-term scenario is an extension of the medium one. At this moment there are no plans for new power plants.

9.2.3 Transport mode

The flow rate of the seven routes for carbon transportation in the Greek Main long-term scenario is constant and is presented in Table 9-9.

Table 9-9: The flow rate for all transportations during the long-term scenario.

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flow rate (Mt/y)	From 2030 to 2050
P#01	4
T#01	0.5
P#02	2
P#03	2
P#04	2
T#02	0.5
P#05	4

In the tables below (Table 9-10, Table 9-11) there are presented some basic design parameters and the key KPIs for the third pipeline (P#03), starting from Ptolemaida V and ending in Volos. Relevant data and respective results were obtained for the rest pipeline connections.

Table 9-10: Basic design parameters of pipeline from E#01 to U#04.

Pipeline basic design parameters	Units	INPUT
Upstream / Inlet / desired - outlet pressure	bar	110 / 130 / 110
Upstream / transport - temperature	°C	31 / 20
Max / Min - pressure allowed	bar	170 / 80
Pipeline length	m	201,157
Elevation difference	m	649
Start year	y	2027
Total number of years	y	24

Table 9-11: Key KPIs of pipeline from emitter to fourth utilization site.

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Key KPIs:		
NPV (costs) in year 2021 (discounted / undiscounted)	€M	26.64 / 91.26
Net CO2 transported	Mt	6.93
CO2 transport costs per ton (discounted / undiscounted)	€/t	3.84 / 13.16

The basic design parameters remain the same for connections identical to the medium-term scenario. Below are presented basic design parameters of the train transportation from Ptolemaida V to HOLCIM – AGET SA (Table 9-12 to Table 9-13)

Table 9-12**:** Basic design parameters of train transport from E#01 to U#05.

Train Basic design parameters	Units	INPUT
Transport pressure	bar	6.5
Transport temperature	°C	-50.3
Wagon capacity	t	240
Distance	m	14,000
Start transport	y	2030
DESIGN		
Travel time per trip	hours	0.23
Total time per trip	hours	10.47
Maximum number of trips per train per year	trips/y	795
Maximum number of wagons per train	-	1
Maximum number of trains	-	1
Transport capacity per wagon	Mt/y	0.19

Table 9-13: Key KPIs of train transport from E#01 to U#05.

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Key KPIs:		
NPV (costs) in year 2021 (discounted/undiscounted)	€M	7.10 / 20.72
Total CO2 transported	Mt	3.04
BioCCS transported	Mt	0.00
Net CO2 transported	Mt	2.99
CO2 transport costs per ton (discounted / undiscounted)	€/t	2.37 / 6.92

9.2.4 CO_2 Utilization

Regarding the CO_2 utilization results for the long-term Main scenario, product KPIs are presented in Table 9-14. From 2030 to 2050, 3.06 Mt CO_2 pure will be produced, 8.42 Mt e-fuels and 299.3 in mineralisation. CO_2 usage for this scenario is presented in Table 9-14. In the long-term scenario, the maximum CO_2 utilization will be done from 2036 to 2050.

Table 9-14: Products KPI for long-term scenario.

Products KPI	Mt (total)	CO_2 used/ton
CO2 pure (food, …)	3.06	2.5
e-fuels	8.41	1.7
mineralization	299.32	0.03

9.2.5 Storage considered in the clusters

In Figure 9-13, the storage scenario for Pentalofos closed storage unit is presented. CO_2 injection will be at the maximum level for the first three years (2030-2033), and following these years, the amount of injected CO_2 will gradually begin to be reduced. Moreover, Figure 9-14 appears the number of wells essential for medium-term scenario implementation.

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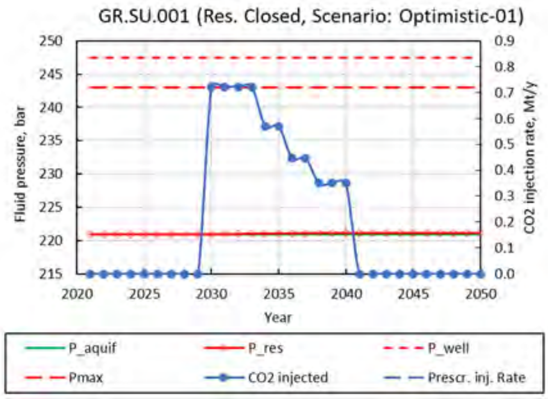

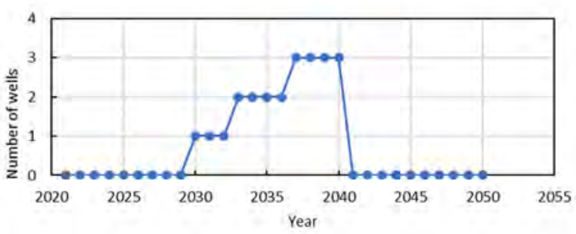

Figure 9-13: Storage medium-term scenario for the West Macedonia area.

Figure 9-14 Number of required wells in the medium-term scenario.

Table 9-13 presents the KPIs for Pentalofos storage unit for medium-term Main scenario (2030-2040). In particular, the total amount of net CO_2 which will be stored is 5.98 Mton, while the total emitted one is 0.03 Mton. Moreover, total undiscounted costs will be 25.6 million euros, whereas the undiscounted CO_2 cost per ton will be up to 4.3 euro per ton.

Table 9-15: KPIs for Pentalofos storage unit in Greek medium-term scenario.

Key KPIs for GR.SU.001, Scenario ID: Optimistic-01	Closed	Unit
NPC in year 2021 (undiscounted / discounted)	-25.6 / -8.8	M€
Total CO_2 stored	5.98	Mton
Total CO_2 emitted	0.03	Mton
CO_2 costs per ton (undiscounted / discounted)	-4.3 / -1.5	€/ton
First year / Last year of full injection	2030 / 2040	yr

Emission benefits from CCUS technology application in West Macedonia area are presented in Figure 9-15 and in Figure 9-5. The environmental CCUS benefits are clear enough in which the CO_2 flows - in this medium-term Main scenario - are depicted in detail.

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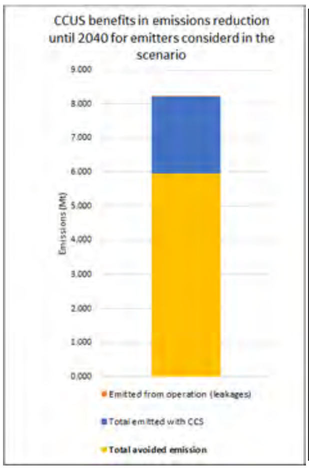

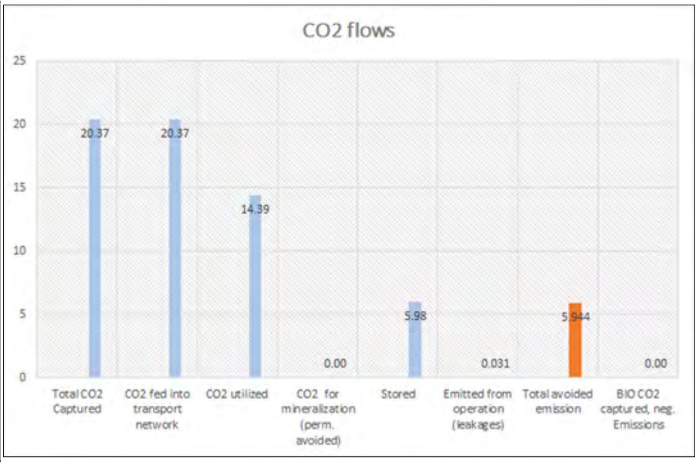

Figure 9-15: Regional emissions reduction until 2040 and

Figure 9-16: CO_2 flows in the medium-term scenario for the West Macedonia area

CCUS West Macedonia KPIs of medium-term scenario are presented inFigure 9-17. This figure includes the analysis of CCS system, of CO_2 volumes and of ETS allowances**. In particular, 20Mt of CO_2 are captured in the medium-term scenario, 20 Mt are transported, 14 Mt are utilised and 6 Mt are stored. The avoided emission is 6 Mt CO_2.**

Figure 9-17 : Region KPIs of medium-term scenario

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-25
Total CAPEX per block	**-12**
Cost of Capture (€/tonCO2 avoided)	-4
Cost of Transport (€/tonCO2 avoided)	-7
Cost of Storage (€/tonCO2 avoided)	-2
OPEX per block	**-13**
Cost of Capture (€/tonCO2 avoided)	-5
Cost of Transport (€/tonCO2 avoided)	-8
Cost of Storage (€/tonCO2 avoided)	0
Transport cost (€/tonCO2 transported)	-4.3
Utilisation (income from CO2 sales) (M€)	1226.4
EUA/ETS credit savings in the region (M€)	379.4

Analysis of CO2 volumes (Mt)

Total CO2 Captured	20.4
CO2 utilized	14.4
CO2 for mineralization (perm. avoided)	0.0
Stored	6.0
Total emitted with CCS	2.3
Total avoided emission	5.9
BIO CO2 captured, neg. Emissions	0.0
Total CO2 fed into transport network	**20**
CCUS National Objectives	200
Share in national objectives	3.0 %

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Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	0
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	1,802.8
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	1,423.4
Cost of CCUS (M€)	150.6
TOTAL costs with CCUS (M€)	**1,573.9**
Cost difference, with minus without CCUS (M€)	**-229.0**
Average yearly energy need, TWh/year	**0.71**
Peak energy need, TWh/year	**1.29**
Breakeven CO2 price (€/tonCO2)	31
First year of profit	2030

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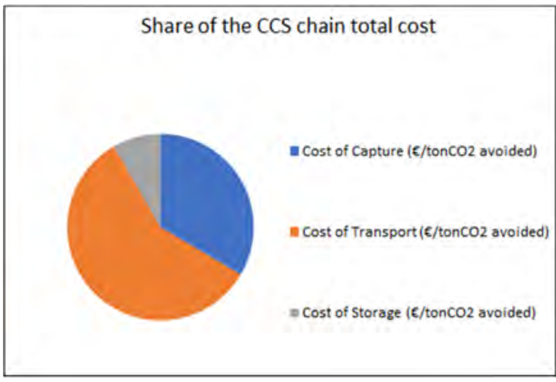
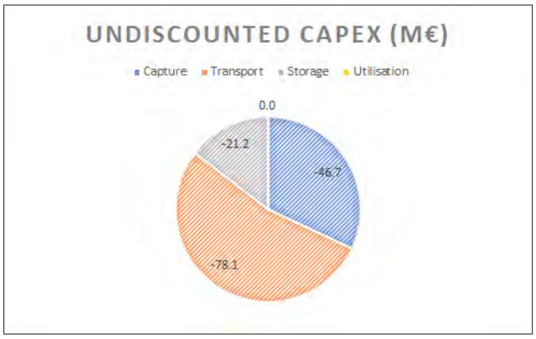


Figure 9-18: Share of CCS total cost, and Figure 9-19 : Total regional costs until 2040.

In the CCS chain total cost, transport has the largest share while storage the smallest one (Figure 9-18). Moreover, CO2 sales and ETS savings generate regional revenues and reduce significantly total costs (Figure 9-18).

The avoided CO_2 emissions from CCUS technology application in West Macedonia are about 6 Mt. Figure 9-20**Erreur ! Source du renvoi introuvable.** shows the undiscounted Capex for West Macedonia which is a) 46.7 million euros in the capture stage, b) 78.1 million euros in the transport stage, c) 21.2 million euros in storage procedure.



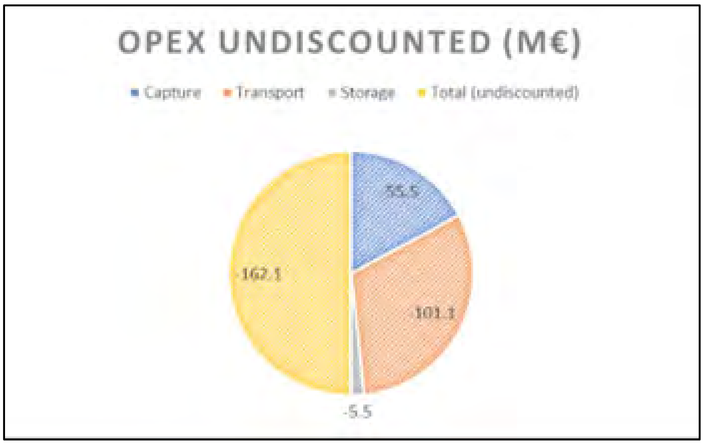


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Figure 9-20: Undiscounted Capex for Greek medium-term Main scenario.

Figure 9-21: Undiscounted Opex for Greek medium-term scenario

The undiscounted Opex for the medium-term Main scenario is 162 million euros.

The fraction CAPEX (euro) per ton of CO_2 avoided is larger in the transport procedure (Figure 9-22).

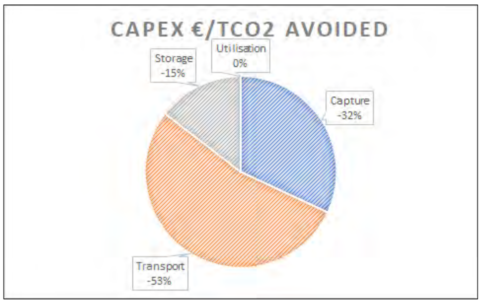

Figure 9-22: CAPEX per avoided CO_2 for Greek medium-term Main scenario.

The regional revenues from CO_2 utilization stage are unambiguous.

Figure 9-23 shows the project costs and incomes for the West Macedonia region per year to implement a medium-term scenario. From 2027 to 2030, most costs will be for the transport procedure, followed by the storage stage. From 2030, the first year of the medium-term Main scenario, West Macedonia Region will start to have incomes from CO_2 sales and, also expenses avoided from EUA savings. Thus, during the medium-term scenario, the regional revenues are much higher than the costs. This means that the mid-term developed scenario is advantageous and profitable for the West Macedonia area both economically and environmentally.

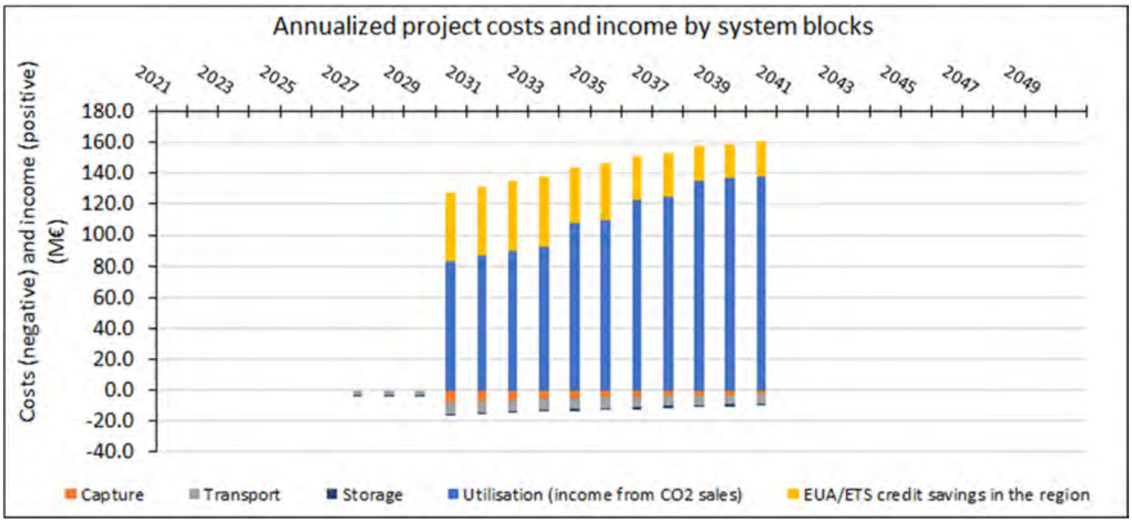

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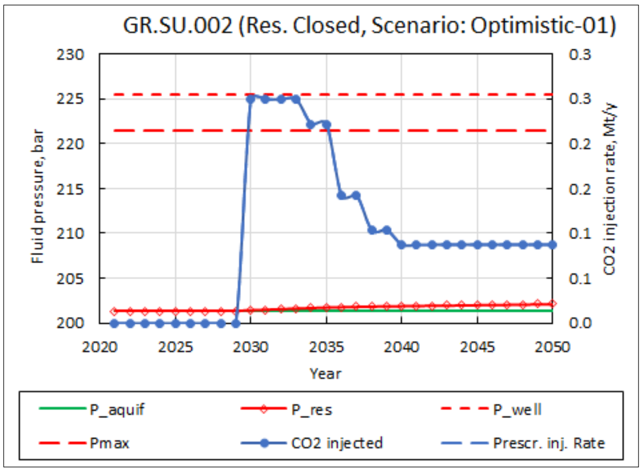
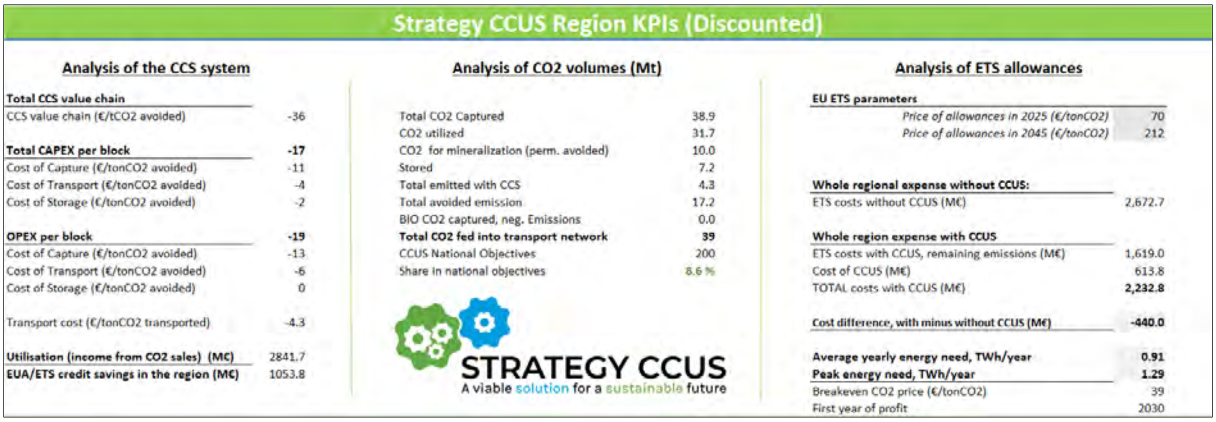
Figure 9-23: Regional costs and incomes for West Macedonia region in medium-term scenario.





Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

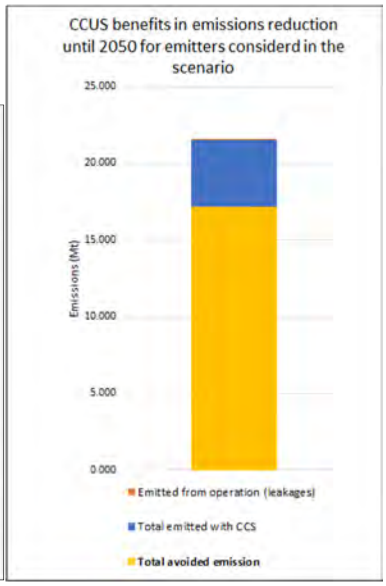
Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-36
Total CAPEX per block	**-17**
Cost of Capture (€/tonCO2 avoided)	-11
Cost of Transport (€/tonCO2 avoided)	-4
Cost of Storage (€/tonCO2 avoided)	-2
OPEX per block	**-19**
Cost of Capture (€/tonCO2 avoided)	-13
Cost of Transport (€/tonCO2 avoided)	-6
Cost of Storage (€/tonCO2 avoided)	0
Transport cost (€/tonCO2 transported)	-4.3
Utilisation (income from CO2 sales) (M€)	2841.7
EUA/ETS credit savings in the region (M€)	1053.8

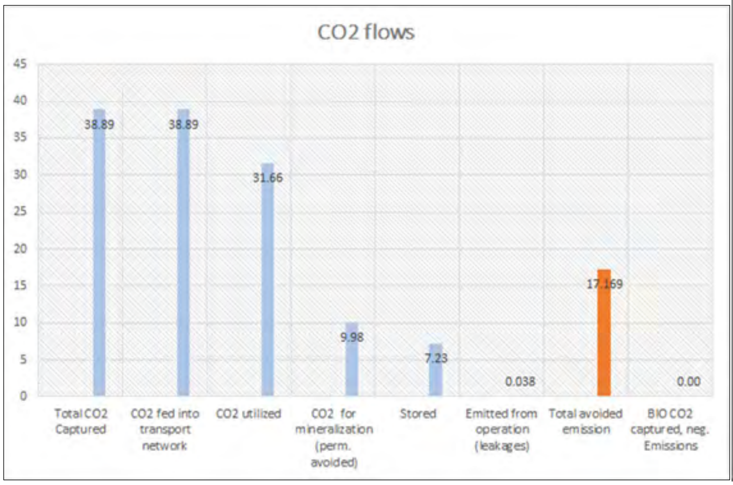
Analysis of CO2 volumes (Mt)

Total CO2 Captured	38.9
CO2 utilized	31.7
CO2 for mineralization (perm. avoided)	10.0
Stored	7.2
Total emitted with CCS	4.3
Total avoided emission	17.2
BIO CO2 captured, neg. Emissions	0.0
Total CO2 fed into transport network	**39**
CCUS National Objectives	200
Share in national objectives	8.6 %

Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	212
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	2,672.7
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	1,619.0
Cost of CCUS (M€)	613.8
TOTAL costs with CCUS (M€)	**2,232.8**
Cost difference, with minus without CCUS (M€)	**-440.0**
Average yearly energy need, TWh/year	**0.91**
Peak energy need, TWh/year	**1.29**
Breakeven CO2 price (€/tonCO2)	39
First year of profit	2030





Western Macedonian Alternative(s) scenario

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9.2.6 Difference with the main

Concerning the alternative scenario, a CO_2-H_2 co-storage is recommended where CO_2 will be acting as cushion gas as it is needed to maintain the pressure in the reservoir. Using CO_2 as a cushion gas for H_2 storage, could be examined as a new technique of storing large amounts of CO_2 to reduce the climate changes in the atmosphere.

The unique properties of CO_2, mainly its super-compressibility through the critical pressure at temperatures just above the critical temperature shows that the performance of CO_2 as a cushion gas in saline aquifers is advantageous for the operator. The use of a gas such as CO_2 may have value for the operator through trading of carbon emission credits.

In a short-term scenario, hydrogen could become competitive in transportation, particularly for large vehicles such as trains and trucks. In a mid-term scenario with the costs of hydrogen production and distribution falling, many more applications should become competitive against low-carbon alternatives and by 2050 total world CO_2 emissions will need to be more than 90 per cent lower- an outcome only achievable by applying low-carbon hydrogen solutions.

9.2.7 KPIs of the Alternative scenario

Hydrogen is a viable solution to the global decarbonisation challenge and the path to increasing cost competitiveness for hydrogen is clear for many applications. A proper revenue and returns on investment can be earned by selling the CO_2 produced and making the air free of pollutants.

9.3 Conclusion of the economic assessment of Western Macedonian area scenarios

Currently, lignite-based is the existing power infrastructure in the West Macedonia region and will be retired by between 2023. The newest CCUS-ready power plant, Ptolemaida 5, is under construction and will be ready in 2023. Initially, it was destined to use lignite for power conversion, however due to changes of the European Environmental Policy, the new plant will be probably converted to natural gas usage. The latter will reduce the CO_2 emissions by 30-50%, still making imminent the use of CO_2 capture due to Emissions Trading System.

In the medium-term scenario, in the CCS chain total cost, transport has the largest share while storage the smallest one. Moreover, CO_2 sales and ETS savings generate regional revenues and reduce significantly total costs.

The regional revenues from CO_2 utilization stage are unambiguous. The revenues per ton of avoided CO_2 appears with the highest utilization procedure. The capture procedure has the higher cost per avoided CO_2 tons.

From 2027 to 2030, most costs will be for the capture procedure, followed by the transport and storage stage. From 2030, the first year of the medium-term scenario, West Macedonia Region will

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start to have incomes from EUA/ETS savings and CO_2 sales. Thus, during the medium-term scenario, the regional revenues are much higher than the costs. This means that the long term developed scenario is advantageous and profitable for the West Macedonia area both economically and environmentally.

The long-term scenario extends the Greek medium-term scenario by ten years, starting from 2030 and ending in 2050, with some key additions. The implementation of a long-term scenario, the West Macedonia region will have revenues up to almost 3.2 billion euros gaining from CO_2 sales and ETS savings. The environmental CCUS benefits are evident. Capture and transport procedures are the most expensive per avoided CO_2 tones.

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10 Poland: economic evaluation of the Upper Silesia basin

10.1 Upper Silesia basin Main Scenario (short- and medium-term)

10.1.1 Cluster(s)r emissions before CCUS

The total CO_2 emissions without CCUS of the Upper Silesia basin in the short- and medium-term scenario 2030 has been estimated at 90.35 Mt.

The number of emissions broken down by emitters is presented in the table below.

Table 10-1 Emissions before CCUS - the Upper Silesia basin.

Emitter ID	Facility name	Tot CO2 emitted if not captured (Mt)
PL.ES.009	Elektrociepłownia Tychy (Zakład Wytwarzania Tychy Tauron Ciepło Sp. z o.o.)	2.04
PL.ES.011	Zakład Wytwarzania Nowa	33.40
PL.ES.016	Nowe Jaworzno	42.30
PL.ES.017	Nowy Rybnik	8.00
PL.ES.014	Elektrownia Koksowni Przyjaźń	2.35
PL.ES.015	Elektrociepłownia Koksowni PRZYJAŹŃ	1.26
PL.ES.018	IGCC Łaziska	1.00
TOTAL		**90.35**

10.1.2 Emitters considered for capture technology

The main information about the used capture technology is presented in the table below.

Table 10-2 Industries with capture.

Industries with capture per hub							
	Elektrociepłownia Tychy (Zakład Wytwarzania Tychy Tauron	Zakład Wytwarzania Nowa	Nowe Jaworzno	Nowy Rybnik	Elektrownia Koksowni Przyjaźń	Elektrociepłownia Koksowni Przyjaźń	IGCC Łaziska

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	Ciepło Sp. z o.o.)						
	PL.ES.009	PL.ES.011	PL.ES.016	PL.ES.017	PL.ES.014	PL.ES.015	PL.ES.018
Sector	energy	energy	energy	energy	energy	energy	energy
Reported emission (Mt/y)	0.20	3.34	4.70	2.00	0.23	0.13	1.00
Total CO_2 captured (from fossil fuel) – Mt CO_2	1.24	3.63	5.11	5.49	1.38	0.77	0.60
Total costs, €/t CO_2 avoided	45.89	172.34	151.35	68.10	92.92	45.12	110.16
Total costs, M€	56.81	625.58	773.12	373.66	128.14	34.61	66.20

10.1.3 Transport mode

The main information about the applied transport mode is presented in the table below.

Table 10-3 Transport mode.

Transport mode								
	Train	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline
From	PL.ES.009	PL.ES.011	PL.ES.016	PL.CH.001	PL.ES.017	PL.UT.002	PL.ES.018	PL.CH.002

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To	PL.UT.001	PL.CH.001	PL.CH.001	PL.SU.004	PL.CH.002	PL.CH.001	PL.CH.002	PL.SU.003
Total CO_2 transported, Mt	1.10	3.34	4.70	8.04	4.00	1.95	0.75	4.75
Total Capex/Opex discounted, €/t CO_2 avoided	7.71	0.23	1.34	4.10	1.40	0.69	4.17	3.31
Total Capex/Opex discounted, M€	8.34	0.76	6.28	32.96	5.59	1.35	3.13	15.72

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10.1.4 CO_2 Utilization

CAPEX and OPEX of the methanol production plant from CO_2 were determined based on literature data [14]. The production of methanol (MeOH) using H_2 and captured CO_2 as raw materials was analysed. The evaluated MeOH plant produces 440 ktMeOH/yr, and its configuration is the result of implementation in CHEMCAD.

For the production volume of 350 ktMeOH/yr, the following cost indicators were adopted:

- Total investment (CAPEX): 175 MEuro,
- FIX OPEX: 224 MEuro/yr.

VARIABLE OPEX of electricity costs were calculated at the level of 4.59 MEuro/yr. This cost was calculated with assumption of energy consumption 106.3 kWh/ton product.

Table 10-4 CO_2 utilization.

CO_2 utilization	From energy production
To industry	Methanol production
Quantities (total production Mt)	2.10
Total CO_2 used (Mt)	3.05
NPV (2020, 8%) - MEuros	-8,031

10.1.5 Storage considered in the clusters

The main information about the applied storage units is presented in the table below.

Table 10-5 Storage.

Storage	Storage A	Storage B
Localisation	Cieszyn-Skoczów-Czechowice PL.SU.003	Częstochowa region PL.SU.004
Start date of storage	2027	2027

[14] Mar Pérez-Fortes, Jan C. Schöneberger, Aikaterini Boulamanti, Evangelos Tzimas: Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. Applied Energy 161 (2016) 718–732

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

Total CO_2 stored	6.09	8.74
Total Capex/Opex undiscounted, M€	206.02	144.22
Total Capex/Opex discounted, M€	50.05	35.04
Total energy used, MWh	36,945.3	51,507.2
CO_2 costs per ton (undiscounted) €/t	34.05	16.60
CO_2 store cost per ton (discounted) €/t	8.27	4.03

10.1.6 KPIs of the scenario

The economic analysis of the scenario 2030 was carried out with calculation assumptions presented in Chapter 2.2 Common Economic data, and following assumptions resulting from the current forecasts and legal regulations for the territory of Poland:

- ✓ Regional CO_2 emission for electricity production in 2021: 671 gCO_2e/kWh,
- ✓ Regional electricity price 2021: 100 €/MWh.

Total discounted CAPEX was estimated at 444.2 M€, including:

- ✓ Capture: 361.9 M€,
- ✓ Transport: 20.4 M€,
- ✓ Storage: 61.9 M€.

The total discounted OPEX for the analysed period amount 240.8 M€, including:

- ✓ Capture: 140.2 M€,
- ✓ Transport: 10.3 M€,
- ✓ Storage: 90.3 M€.

Therefore, the total discounted CAPEX and OPEX amount to 685.0 M€.

Per 1 ton of CO_2 avoided, the total discounted CAPEX and OPEX are 45.46 €/ton CO_2 calculated, including:

- ✓ Capture: 33.32 €/ton CO_2,
- ✓ Transport: 2.04€/ton CO_2,
- ✓ Storage: 10.10 €/ton CO_2.

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In the scenario with CCUS, the discounted ETS costs to emit non-captured CO_2 were calculated at 5,702.87 M€. The total cost of the CCUS scenario is thus 6,387.89 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 6,651.23 M€. This means that the scenario with CCUS is more expensive than the scenario without CCUS by 263.00 M€. The calculation results are presented graphically in the diagrams below.

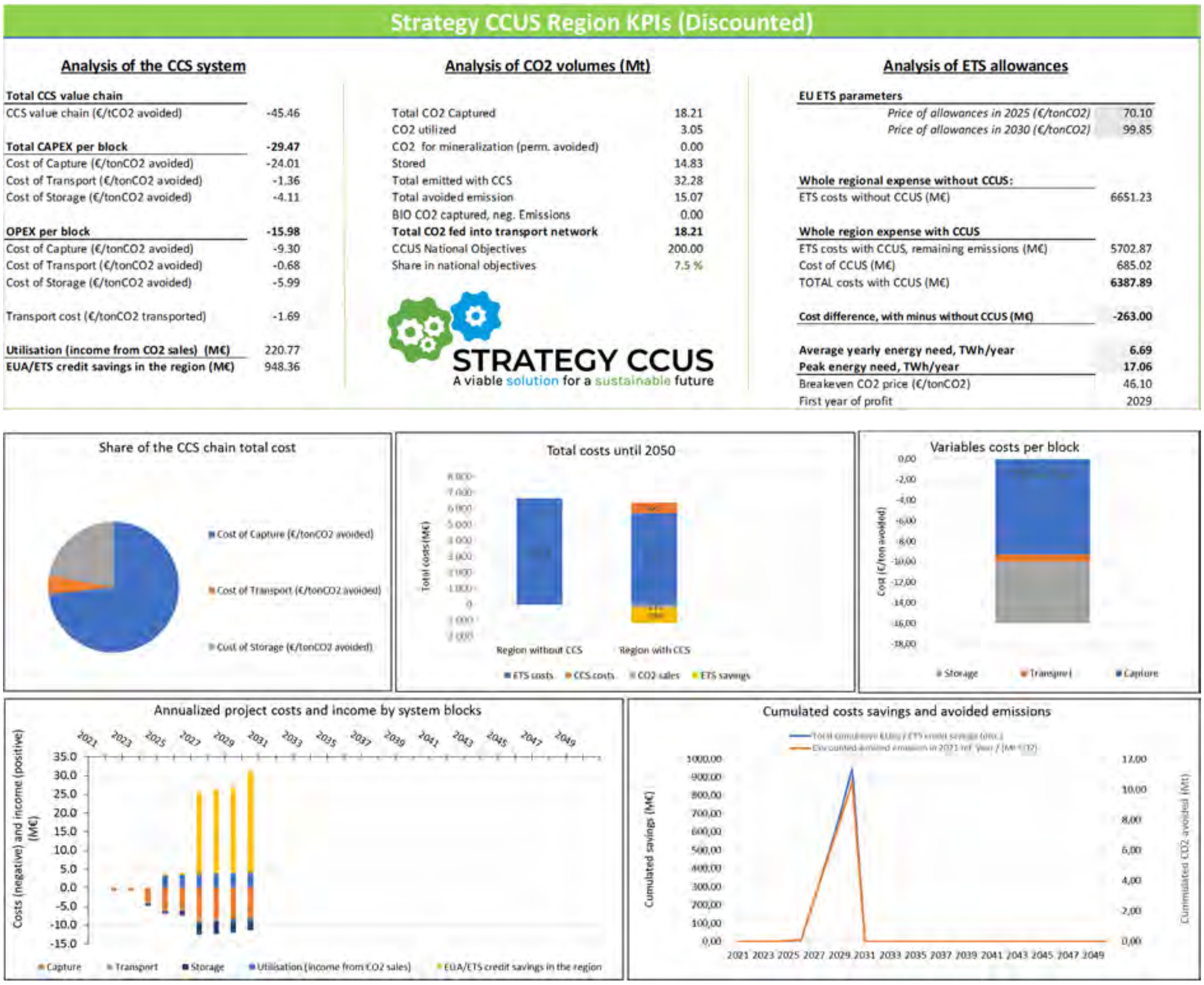

Figure 10-1: **Overall cost analysis of the CCUS chain in Upper Silesia basin: main scenario (short- and medium-term)**

The positive economic result of the CCUS scenario was decisively influenced by projected very high prices increase of allowances for CO_2 emission (99.85 €/tonCO_2 in 2030). The CAPEX of the CO_2 capture installations are the main component of the total cost of the scenario. They constitute as much as 64.8% of the sum of discounted capital expenditures and operating costs. The operating costs of CO_2 capture installations are also significant: they account for approximately 20.5% of the discounted operating costs. The total ETS costs constitute as much as 89.3% of the total costs of this scenario with CCUS.

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10.2 Upper Silesia basin Main Long-term scenario 2050

10.2.1 Cluster(s)r emissions before CCUS

The total CO_2 emissions without CCUS of the Upper Silesia basin in the Main Long-term scenario 2050 has been estimated at 322.45 Mt.

The amount of emissions broken down by emitters is presented in the table below.

Table 10-6 Emissions before CCUS - the Upper Silesia basin.

Emitter ID	Facility name	Tot CO_2 emitted if not captured (Mt)
PL.ES.009	Elektrociepłownia Tychy (Zakład Wytwarzania Tychy Tauron Ciepło Sp. z o.o.)	6.11
PL.ES.011	Zakład Wytwarzania Nowa	100.20
PL.ES.016	Nowe Jaworzno	136.30
PL.ES.017	Nowy Rybnik	48.00
PL.ES.014	Elektrownia Koksowni Przyjaźń	7.05
PL.ES.015	Elektrociepłownia Koksowni PRZYJAŹŃ	3.79
PL.ES.018	IGCC Łaziska	21.00
TOTAL		**322.45**

10.2.2 Emitters considered for capture technology

The main information about the used capture technology is presented in the table below.

Table 10-7 Industries with capture.

Industries with capture per hub	Elektrociepłownia Tychy (Zakład Wytwarzania Tychy Tauron Ciepło Sp. z o.o.)	Zakład Wytwarzania Nowa	Nowe Jaworzno	Nowy Rybnik	Elektrownia Koksowni Przyjaźń	Elektrociepłownia Koksowni Przyjaźń	IGCC Łaziska
	PL.ES.009	PL.ES.011	PL.ES.016	PL.ES.017	PL.ES.014	PL.ES.015	PL.ES.018
Sector	energy	energy	energy	energy	energy	energy	energy

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Reported emission (Mt/y)	0.20	3.34	4.70	2.00	0.23	0.13	1.00
Total CO_2 captured (from fossil fuel) – Mt CO_2	5.4	19.1	26.8	32.9	6.0	3.3	12.6
Total costs, €/t CO_2 avoided	17.56	41.28	37.03	23.55	26.24	18.81	9.60
Total costs, M€	94.22	786.74	993.16	775.21	156.81	62.50	121.13

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10.2.3 Transport mode

The main information about the applied transport mode is presented in the table below.

Table 10-8 Transport mode.

Transport mode	Train	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline
From	PL.ES.009	PL.ES.011	PL.ES.016	PL.CH.001	PL.ES.017	PL.UT.002	PL.ES.018	PL.CH.002
To	PL.UT.00 1	PL.CH.001	PL.CH.001	PL.SU.004	PL.CH.002	PL.CH.001	PL.CH.002	PL.SU.003
Total CO_2 transported, Mt	4,77	17,53	24,68	42,21	24,00	8,45	15,75	39,74
Total Capex/Opex discounted, €/t CO_2 avoided	1.61	0.02	0.15	0.48	0.12	0.08	0.11	0.22
Total Capex/Opex discounted, M€	7.56	0.40	3.72	20.12	2.99	0.68	1.68	8.87

10.2.4 CO_2 Utilization

CAPEX and OPEX of the methanol production plant from CO_2 were determined based on literature data [15]. The production of methanol (MeOH) using H_2 and captured CO_2 as raw materials was analysed. The evaluated MeOH plant produces 440 ktMeOH/yr, and its configuration is the result of implementation in CHEMCAD.

For the production volume of 350 ktMeOH/yr, the following cost indicators were adopted:

- Total investment (CAPEX): 175 MEuro,
- FIX OPEX: 224 MEuro/yr.

VARIABLE OPEX of electricity costs were calculated in the tool at the level of 4.59 MEuro/yr. This cost was calculated with assumption of energy consumption 106.3 kWh/ton product.

[15] Mar Pérez-Fortes, Jan C. Schöneberger, Aikaterini Boulamanti, Evangelos Tzimas: Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. Applied Energy 161 (2016) 718–732

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

Table 10-9 CO_2 utilization.

CO2 utilization	From energy production
To industry	Methanol production
Quantities (total production Mt)	9.12
Total CO_2 used	13.22

10.2.5 Storage considered in the clusters

The main information about the applied storage units is presented in the table below.

Table 10-10 Storage.

Storage	Storage A	Storage B
Localisation	Cieszyn-Skoczów-Czechowice PL.SU.003	Częstochowa region PL.SU.004
Start date of storage	2027	2027
Total CO_2 stored	45.54	45.87
Total Capex/Opex undiscounted, M€	523.81	374.05
Total Capex/Opex discounted, M€	127.26	90.88
Total energy used, MWh	274,350.5	268.998.5
CO_2 costs per ton (undiscounted) €/t	11.50	8.15
CO_2 store cost per ton (discounted) €/t	2.88	1.99

10.2.6 KPIs of the scenario

The economic analysis of the long-term scenario 2050 was carried out with the following calculation assumptions, resulting from the current forecasts and legal regulations for the territory of Poland:

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- ✓ Business tax level (income from revenue creation): 19.0%,
- ✓ Regional CO_2 emission for electricity production in 2021: 671 gCO_2e/kWh,
- ✓ Regional electricity price 2021: 100 €/MWh.

Total discounted CAPEX was estimated at 1,289.8 M€, including:

- ✓ Capture: 990.7M€,
- ✓ Transport: 61.0 M€,
- ✓ Storage: 238.2 M€.

The total discounted OPEX for the analysed period amount to 1,054.3 M€, including:

- ✓ Capture: 586.9 M€,
- ✓ Transport: 43.3 M€,
- ✓ Storage: 424.1 M€.

Therefore, the **total discounted CAPEX and OPEX amount to 2,344.2 M€.**

Per 1 ton of CO_2 avoided, the total discounted CAPEX and OPEX are 25.39 €/ton CO_2 calculated, including:

- ✓ Capture: 17.09 €/ton CO_2,
- ✓ Transport: 1.13 €/ton CO_2,
- ✓ Storage: 7.17 €/ton CO_2.

In the scenario with CCUS, the discounted ETS costs to emit non-captured CO_2 were calculated at 16,033.28 M€. The total cost of the CCUS scenario is thus 18,377.46 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 22,184.65 M€. This means that the scenario without CCUS is more expensive than the scenario with CCUS by 3,807.00 M€. The calculation results are presented graphically in the diagrams below.

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-25.39
Total CAPEX per block	**-13.97**
Cost of Capture (€/tonCO2 avoided)	-10.73
Cost of Transport (€/tonCO2 avoided)	-0.66
Cost of Storage (€/tonCO2 avoided)	-2.58
OPEX per block	**-11.42**
Cost of Capture (€/tonCO2 avoided)	-6.36
Cost of Transport (€/tonCO2 avoided)	-0.47
Cost of Storage (€/tonCO2 avoided)	-4.59
Transport cost (€/tonCO2 transported)	-0.98
Utilisation (income from CO2 sales) (M€)	1328.70
EUA/ETS credit savings in the region (M€)	6151.36

Analysis of CO2 volumes (Mt)

Total CO2 Captured	106.08
CO2 utilized	13.22
CO2 for mineralization (perm. avoided)	0.00
Stored	91.42
Total emitted with CCS	176.38
Total avoided emission	92.31
BIO CO2 captured, neg. Emissions	0.00
Total CO2 fed into transport network	**106.08**
CCUS National Objectives	200.00
Share in national objectives	46.2 %

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Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70.10
Price of allowances in 2050 (€/tonCO2)	249.85
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	22184.65
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	16033.28
Cost of CCUS (M€)	2344.18
TOTAL costs with CCUS (M€)	**18377.46**
Cost difference, with minus without CCUS (M€)	**-3807.00**
Average yearly energy need, TWh/year	**12.25**
Peak energy need, TWh/year	**17.06**
Breakeven CO2 price (€/tonCO2)	28.70
First year of profit	2029

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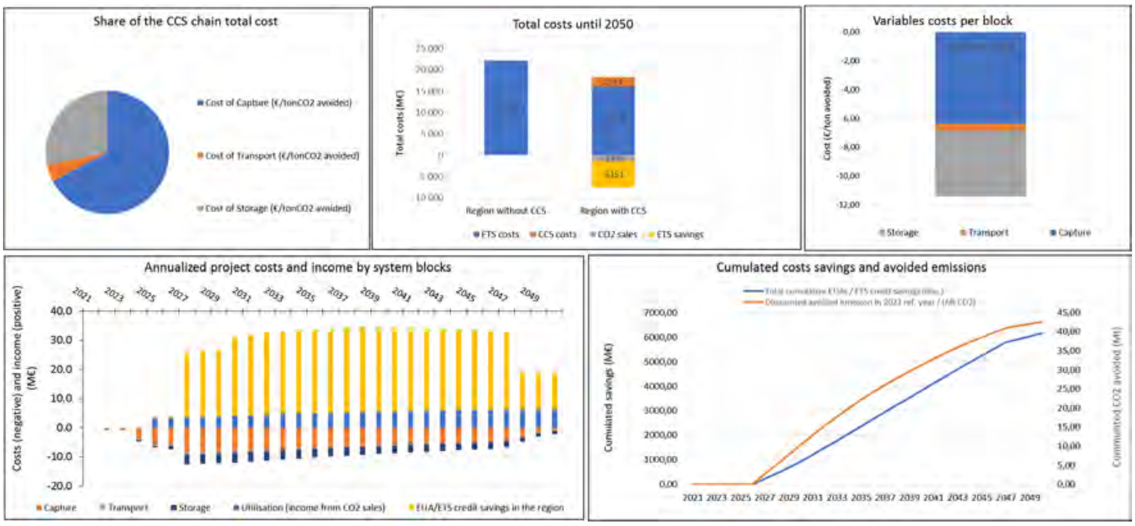

Figure 10-2: Overall cost analysis of the CCUS chain in Upper Silesia basin: long-term scenario 2050

2050The positive economic result of the CCUS scenario was decisively influenced by projected very high prices increase of allowances for CO_2 emission (249.85 €/tonCO_2 in 2050) and long service life of the CO_2 capture installations. The CAPEX of the CO_2 capture installations is the main component of the total cost of the scenario. The total ETS costs constitute as much as 87.2% of the total costs of this scenario with CCUS.

10.3 Upper Silesia basin Alternative(s) scenario

10.3.1 Difference with the main

The analyses were performed with the same calculation assumptions as for the Main Long-term scenario 2050. The differences between the alternative scenarios relate to the calculation of OPEX and, consequently, CAPEX.

10.3.2 KPIs of the Alternative scenario

Scenario 01: Increased capture from Nowe Jaworzno power plant, scenario without the power plant IGCC Łaziska

Total discounted CAPEX of the Alternative Scenario 01 was estimated at 982.1 M€, including:

- ✓ Capture: 675.9 M€,
- ✓ Transport:56.2 M€,
- ✓ Storage: 250.1 M€.

The total discounted OPEX of the Alternative Scenario 01 for the analysed period amount 922.2 M€, including:

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- ✓ Capture: 453.5 M€,
- ✓ Transport: 39.5 M€,
- ✓ Storage: 429.2 M€.

Therefore, the total discounted CAPEX and OPEX amount to 1,904.3 M€.

Per 1 ton of CO_2 avoided, the total discounted CAPEX and OPEX of the Alternative Scenario 01 are 19.99 €/ton CO_2 calculated, including:

- ✓ Capture: 11.86 €/ton CO_2,
- ✓ Transport: 1.00 €/ton CO_2,
- ✓ Storage: 7.13 €/ton CO_2.

In the scenario 01: with CCUS, the discounted ETS costs to emit non-captured CO_2 were calculated at 7,548.09 M€. The total cost of the CCUS scenario is thus 9,452.44 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 13,888.20 M€. This means that the scenario without CCUS is more expensive than the scenario with CCUS by 4,436.00 M€. The calculation results are presented graphically in the diagrams below.

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-19.99
Total CAPEX per block	**-10.31**
Cost of Capture (€/tonCO2 avoided)	-7.10
Cost of Transport (€/tonCO2 avoided)	-0.59
Cost of Storage (€/tonCO2 avoided)	-2.63
OPEX per block	**-9.68**
Cost of Capture (€/tonCO2 avoided)	-4.76
Cost of Transport (€/tonCO2 avoided)	-0.41
Cost of Storage (€/tonCO2 avoided)	-4.51
Transport cost (€/tonCO2 transported)	-0.88
Utilisation (income from CO2 sales) (M€)	1328.70
EUA/ETS credit savings in the region (M€)	6340.12

Analysis of CO2 volumes (Mt)

Total CO2 Captured	109.02
CO2 utilized	13.22
CO2 for mineralization (perm. avoided)	0.00
Stored	93.98
Total emitted with CCS	80.38
Total avoided emission	95.24
BIO CO2 captured, neg. Emissions	0.00
Total CO2 fed into transport network	**109.02**
CCUS National Objectives	200.00
Share in national objectives	47.6 %

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Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70.10
Price of allowances in 2050 (€/tonCO2)	249.85
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	13888.20
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	7548.09
Cost of CCUS (M€)	1904.35
TOTAL costs with CCUS (M€)	**9452.44**
Cost difference, with minus without CCUS (M€)	**-4436.00**
Average yearly energy need, TWh/year	**7.62**
Peak energy need, TWh/year	**10.45**
Breakeven CO2 price (€/tonCO2)	23.78
First year of profit	2028

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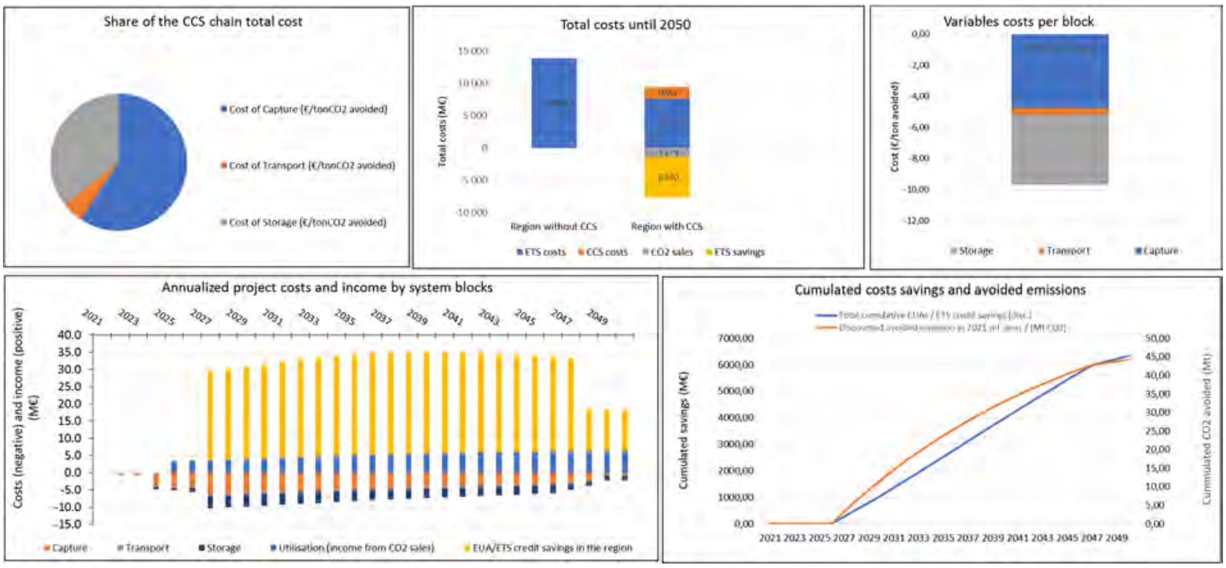

Figure 10-3: Overall cost analysis of the CCUS chain in Upper Silesia basin: alternative scenario 01

The positive economic result of the CCUS scenario was decisively influenced by projected very high prices increase of allowances for CO_2 emission (249.85 €/tonCO_2 in 2050 against 46.30 €/tonCO_2 in 2021) and long service life of the CO_2 capture installations. The CAPEX of the CO_2 capture installations is the main component of the total cost of the scenario. The total ETS costs with CCUS constitute as much as 79.9% of the total costs of this scenario with CCUS.

Scenario 02: Transport via pipeline instead of rail from the heating plant at Tychy to methanol plant Synthos

Total discounted CAPEX of the Alternative Scenario 02 was estimated at 1,289.6 M€, including:

- ✓ Capture: 990.7 M€,
- ✓ Transport: 60.7 M€,
- ✓ Storage: 38.2 M€.

The total discounted OPEX of the Alternative Scenario 02 for the analysed period amount 1,043.2 M€, including:

- ✓ Capture: 586.9 M€,
- ✓ Transport: 32.2 M€,
- ✓ Storage: 424.1 M€.

Therefore, the total discounted CAPEX and OPEX amount to 2,332.8 M€.

Per 1 ton of CO_2 avoided, the total discounted CAPEX and OPEX of the Alternative Scenario 02 are 25.27 €/ton CO_2 calculated, including:

- ✓ Capture: 17.09 €/ton CO_2,

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- ✓ Transport: 1.01 €/ton CO_2,
- ✓ Storage: 7.17 €/ton CO_2.

In the scenario with CCUS, the discounted ETS costs to emit non-captured CO_2 were calculated at 16,033.28 M€. The total cost of the CCUS scenario is thus 18,366.06 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 22,184.65 M€. This means that the scenario without CCUS is more expensive than the scenario with CCUS by 3,819.00 M€. The calculation results are presented graphically in the diagrams below.

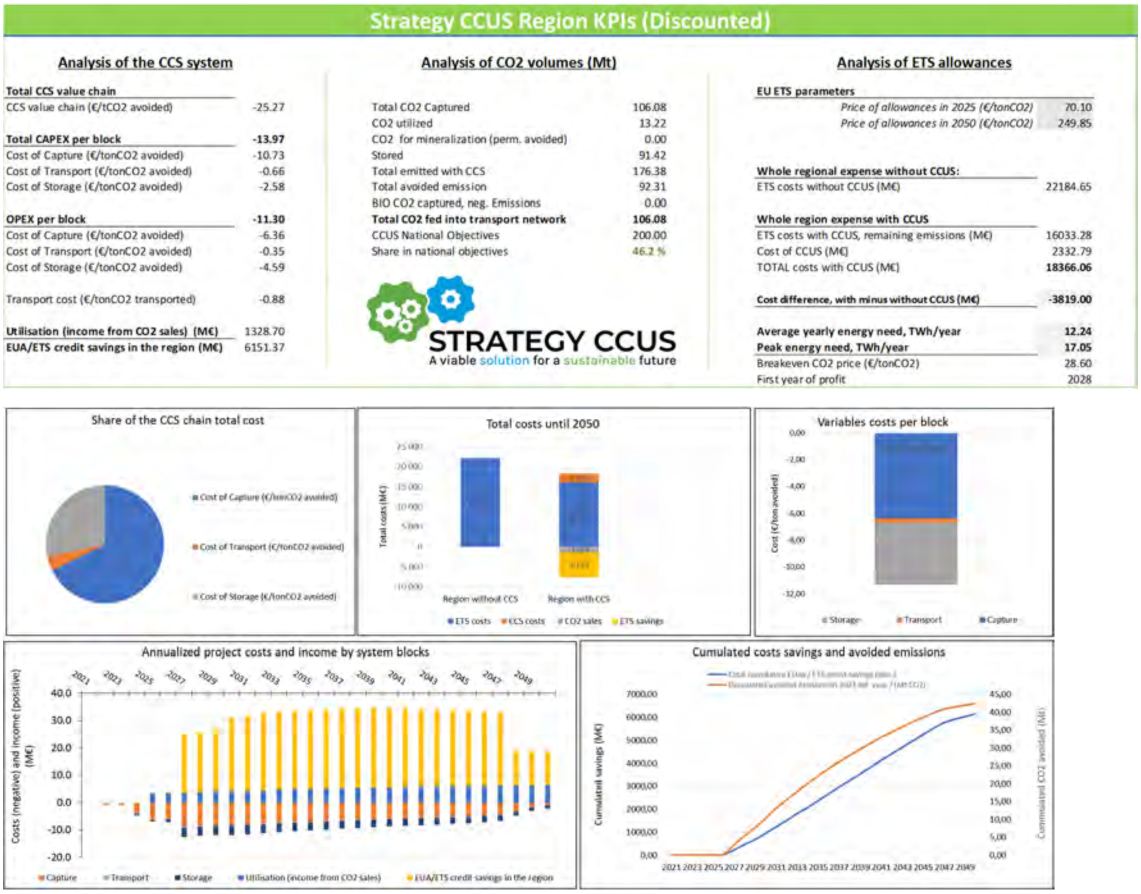

Figure 10-4: Overall cost analysis of the CCUS chain in Upper Silesia basin: alternative scenario 02

02

The positive economic result of the CCUS scenario was decisively influenced by projected very high prices increase of allowances for CO_2 emission (249.85 €/tonCO_2 in 2050 against 46.30 €/tonCO_2 in 2021) and long service life of the CO_2 capture installations. The CAPEX of the CO_2 capture installations is the main component of the total cost of the scenario. The total ETS costs with CCUS constitute as much as 87.3% of the total costs of this scenario with CCUS.

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Scenario 03: Increased capture from Nowe Jaworzno power plant, scenario without power plants: IGCC Łaziska and CCGT Rybnik

Total discounted CAPEX of the Alternative Scenario 03 was estimated at 811.8 M€, including:

- ✓ Capture: 513.3 M€,
- ✓ Transport: 73.4 M€,
- ✓ Storage: 225.1 M€.

The total discounted OPEX of the Alternative Scenario 03 for the analysed period amount 687.1 M€, including:

- ✓ Capture: 208.8 M€,
- ✓ Transport: 48.7 M€,
- ✓ Storage: 429.5 M€.

Therefore, the total discounted CAPEX and OPEX amount to 1,498.9 M€.

Per 1 ton of CO_2 avoided, the total discounted CAPEX and OPEX of the Alternative Scenario 03 are 17.28 €/ton CO_2 calculated, including:

- ✓ Capture: 8.32 €/ton CO_2,
- ✓ Transport: 1.41 €/ton CO_2,
- ✓ Storage: 7.55 €/ton CO_2.

In the scenario with CCUS, the discounted ETS costs to emit non-captured CO_2 were calculated at 4,264.09 M€. The total cost of the CCUS scenario is thus 5,762.94 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated 10,064.89 M€. This means that the scenario without CCUS is more expensive than the scenario with CCUS by 4,302.00 M€. The calculation results are presented graphically in the diagrams below.

Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-17.28
Total CAPEX per block	**-9.36**
Cost of Capture (€/tonCO2 avoided)	-5.92
Cost of Transport (€/tonCO2 avoided)	-0.85
Cost of Storage (€/tonCO2 avoided)	-2.60
OPEX per block	**-7.92**
Cost of Capture (€/tonCO2 avoided)	-2.41
Cost of Transport (€/tonCO2 avoided)	-0.56
Cost of Storage (€/tonCO2 avoided)	-4.95
Transport cost (€/tonCO2 transported)	-1.22
Utilisation (income from CO2 sales) (M€)	1328.70
EUA/ETS credit savings in the region (M€)	5800.80

Analysis of CO2 volumes (Mt)

Total CO2 Captured	100.48
CO2 utilized	13.22
CO2 for mineralization (perm. avoided)	0.00
Stored	85.82
Total emitted with CCS	23.08
Total avoided emission	86.75
BIO CO2 captured, neg. Emissions	0.00
Total CO2 fed into transport network	**100.48**
CCUS National Objectives	200.00
Share in national objectives	43.4 %

STRATEGY CCUS
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Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70.10
Price of allowances in 2050 (€/tonCO2)	249.85
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	10064.89
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	4264.09
Cost of CCUS (M€)	1498.85
TOTAL costs with CCUS (M€)	**5762.94**
Cost difference, with minus without CCUS (M€)	**-4302.00**
Average yearly energy need, TWh/year	**6.26**
Peak energy need, TWh/year	**8.74**
Breakeven CO2 price (€/tonCO2)	20.60
First year of profit	2027

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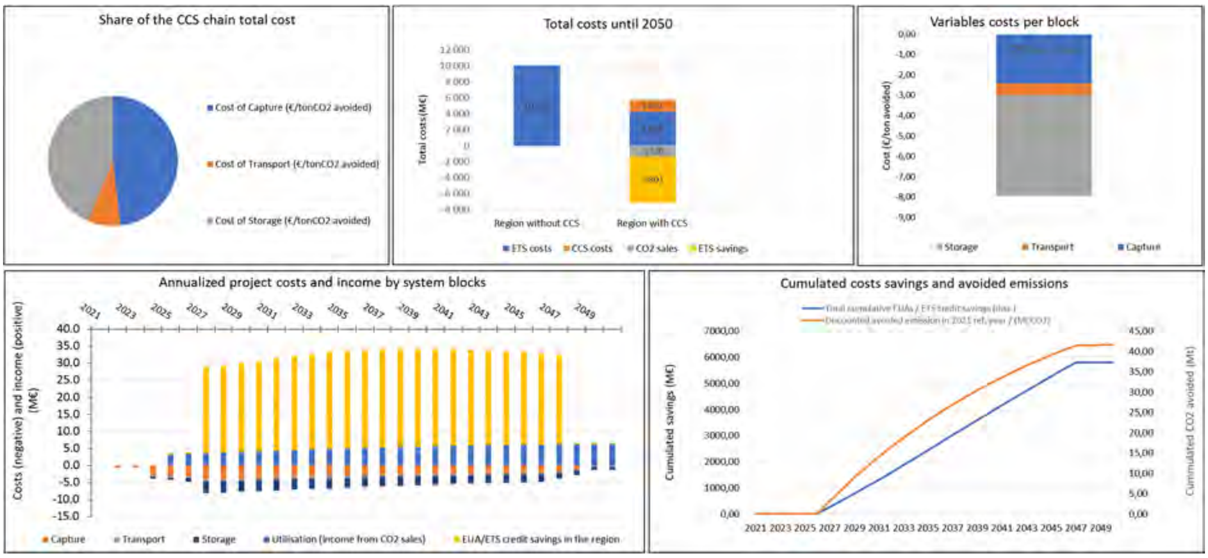

Figure 10-5: Overall cost analysis of the CCUS chain in Upper Silesia basin: alternative scenario 0303

The positive economic result of the CCUS scenario was decisively influenced by projected very high prices increase of allowances for CO_2 emission (249.85 €/tonCO_2 in 2050 against 46.30 €/tonCO_2 in 2021) and long service life of the CO_2 capture installations. The CAPEX of the CO_2 capture installations are the main component of the total cost of the scenario. The total ETS costs constitute as much as 74.0% of the total costs of this scenario with CCUS.

10.4 Conclusion of the economic assessment of Upper Silesia scenarios

Taking into account the total discounted CAPEX and OPEX calculated per 1 ton of CO_2 avoided, the cost of the scenario 03 "Increased capture from Nowe Jaworzno power plant, scenario without power plants: IGCC Łaziska and CCGT Rybnik is the most economic-effective scenario. This scenario generates 4,302.00 M€ savings in relation to the scenario without CCUS.

On the other hand, the least economic-effective in terms of discounted CAPEX and OPEX calculated per 1 ton of CO_2 avoided is the main short-term Scenario 2030. The reason is that the service life of the expensive CCUS infrastructure is too short in reference to CO_2 avoided.

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11 Conclusion

A preliminary and obvious conclusion drawn from this work is: **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 for example, **all scenarios are specific to the region** and to the national public policies in place which influence them.

Similarly, it is very relevant to insist on the fact that **there is not only ONE cost of CCUS,** but specific costs related to each of the deployed scenarios expressed per ton of CO_2 avoided.

Over an economic evaluation period of this magnitude, i.e., 25 years for the long-term scenarios, the investment costs are distributed per ton of CO_2 avoided over the entire period. 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 the regional lessons that can be learned from them.

Considering the financial gap between CCUS costs and European Union - Emissions Trading System (EU-ETS), three long-term scenarios among those evaluated make CCUS more attractive: (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 the estimated EU ETS compliance costs.

These results are however 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 Rhone 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 that is the highest.

The deployment and technical-economic analysis of the eight CCUS chains in Southern and Eastern Europe have **yielded numerous lessons**. Among them we can mention:

- ✓ As a matter of course, the **existing physical characteristics** of each of the eight regions, 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 deployments of CCUS.**

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- ✓ Across the eight regions, nearly **78% of the CO_2 captured is ultimately avoided** once the CO_2 used in the production of fast-moving consumer goods is released to the atmosphere. This ratio should be seen with great attention in terms of efficiency when deploying CCUS.
- ✓ Among the eight scenarios**, Ebro Basin** is the most efficient scenario with **0.955 tons of CO_2 avoided per ton of CO_2 captured.**
- ✓ Each scenario has its own **efficiency in terms of Euros per tons of avoided CO_2** and this efficiency 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, reduces the costs of CO_2 storage and increases the revenues of the CCUS chain. It should be promoted.
- ✓ In average, **OPEX costs account for 63% of total CCUS costs**. This expense item should be reduced as a priority to reduce the costs of the CCUS chain.
- ✓ Capture costs for industries other than power plants are higher, which has a significant impact on the costs of the entire CCUS chain (capture costs generally represent a significant portion of total costs – 32% in average). **Capture costs for industries with high CO_2 emissions other than power plants** must be reduced in the future to limit the costs of the CCUS chain.
- ✓ When **bioCO_2 is captured**, it is essential to trace the use of this bioCO_2 to certify whether it is a negative emission or not. Indeed, when captured bioCO_2 is stored in geological reservoirs or used in long-lived products such as mineralization, it may be considered a negative CO_2 emission. On the other hand, when the captured bioCO_2 is used in short-lived products such as synthetic fuels, it should be considered as avoided. Additional LCA-based analyses are needed to assess the net emissions avoided or removed.
- ✓ The pooling of investment costs, particularly infrastructure costs, makes it possible to reduce the costs of the CCUS chain

To properly incentivise CCUS scenarios, it is important to consider a set of parameters, namely:

- ✓ the **environmental impact of CCUS** in terms of the volume of CO_2 avoided during the scenario,
- ✓ the **efficiency of CCUS** through the total investment costs per tonne of CO_2 avoided,
- ✓ the **reuse made of the captured CO_2**, in particular the uses of CO_2 in long-life products that should be incentivised, and
- ✓ the **share of captured bioCO_2 and its storage and use** in long-life products to favour negative CO2 emissions.

In the eight regions studied, common outcomes can be highlighted related to the economic analysis such as:

- ✓ industrial sector and the Administrations should unify their strategies and roadmaps, to make common investments and reduce the CAPEX specially in pipeline transport network

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- ✓ economic study of the scenarios would benefit from a sensitivity analysis of the various investment and operational parameters of the CCUS modules due to the uncertainties, for instance, in terms of efficiencies of CO_2 capture technologies, as well as the low maturity level of the storage resources (Tier 1 and Tier 2), and
- ✓ an in deep and more detailed economic analyses should be conducted to reduce the economics uncertainties of the evaluation based on literature costs.

All these parameters should be encouraged, and they are highly dependent on the regional characteristics of fossil energy production and consumption.

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