D5.4 - Transnational scenarios report

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Executive summary

The objective of the Task 5.3 "Economic evaluation of national and transnational scenarios" is to propose transnational scenarios between the eight regions studied in the project. For this, we base our study on the eight regional analyses presented in the report "Deliverable D5.3: Economic Evaluation of CCUS Scenarios in Eight Southern European Regions" (Coussy et al., 2022), and the data available from the database resulting from WP2 (Mesquita & Carneiro, 2020). Each regional study has provided a main scenario that reflects a good match between the volumes that can be captured in the industries and the regional storages, while taking care to optimize the transport network.

These regional analyses show that some regions are constrained by their storage capacity. Moving on to the transnational economic analysis will allow us to discuss whether these constraints can be relieved by, for example, capturing CO_2 in one region and storing it in another one. We also consider more complex configurations where the captured CO_2 would be transported from several regions to a single storage site.

Our working method is based on the regional scenarios (1) we identify the regions that exhibit limited storage capacities qualified by their storage filling rate by 2050, (2) we identify the regions characterized by high capacity storage facilities and that still have significant available capacities in 2050; (3) finally, based on geographical arguments, we identify pairs or trios of regions that could form clusters so as to avoiding transporting CO_2 over too long distances. In doing so, we ensured the use and expansion of existing or planned infrastructures between regions, and the use of common storage sites.

Thus, we propose to transport the CO_2 captured in Upper Silesia to northern Croatia (scenario for Central Europe), the CO_2 captured in the Rhone valley to the Ebro region, and a variant of this scenario by transporting the CO_2 from the Rhone Valley and the Ebro region to the western Macedonia. Interestingly, transnational scenarios give more flexibility to the CCUS chain by avoiding storage capacity constraints in highly industrialized regions. By lifting the limitation on the storage capacity, it is even possible to increase the quantities of CO_2 captured by :

- x2 for the Upper Silesia / Northern Croatia scenario
- +27% for the Rhone Valley / Ebro / Western Macedonia scenario

With these three transnational scenarios, the total quantities of CO_2 captured for 4 regions exceed 400 Mt, i.e., more than for the 8 initial regions.

If, from the point of view of the physical quantities of CO_2 captured and transported, the transnational scenarios are of real interest for the planet, the economic analysis of the transnational scenarios does not make it possible to highlight the effects of scale on the cost of the ton of CO_2 avoided. The costs obtained are comparable to those resulting from the regional analyses and remain relatively low. Unsurprisingly, transnational scenarios increase transport costs, especially when using ships.

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1 Introduction

1.1 Aims of the task

The objective of the task is to propose transnational scenarios between the eight regions studied in the project (

Table 1-1). For this, we base our study on the eight regional analyses presented in the report "Deliverable D5.3: Economic Evaluation of CCUS Scenarios in Eight Southern European Regions" (Coussy et al., 2022), and the data available from the database resulting from WP2 (Mesquita & Carneiro, 2020). Each regional study has provided a main scenario that reflects a good match between the volumes that can be captured in the industries and the regional storages, while taking care to optimize the transport network.

These regional analyses show that some regions have constraints due to limited storage capacity. Moving on to the transnational economic analysis will allow us to discuss whether these constraints can be relieved by, for example, capturing CO_2 in one region and storing it in a second one. We also consider more complex configurations by transporting the captured CO_2 from several regions to a single storage site.

Our working method is based on the regional scenarios (1) we identify the regions that exhibit limited storage capacities qualified by their storage filling rate by 2050, (2) we identify the regions characterized by high capacity storage facilities and that still have significant available capacities in 2050; (3) finally, based on geographical arguments, we identify pairs or trios of regions that could form clusters so as to avoiding transporting CO_2 over too long distances. In doing so, we ensured the use and expansion of existing or planned infrastructures between regions, and the use of common storage sites.

Finally, the transnational analyses are conducted and evaluated from an economic point of view with the tool developed in the project (Nermoen et al, 2022) and which was used for performing the regional analyses. By proceeding in this way, we ensure consistency in the costs presented and can legitimately compare certain KPIs between the regional and transnational analyses.

1.2 Results of the regional assessments

1.2.1 Regions with limited storage capacities

Figure 1 presents a map of Europe with all the storage sites considered in the eight regional scenarios. Each site is represented by a circle whose size depends on the forecasted quantity of CO_2 stored in 2050 and whose color depends on the storage filling rate in 2050. The filling rate is calculated according to the following formula:

Filling rate (%) = Stored CO_2 / Storage Capacity x 100

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The scale associated with the fill rates goes from blue (space available) to red (storage filled). There are several red circles appearing on the map, in the Upper Silesia, Rhone Valley, and Paris Basin regions due to the lack of storage capacity. In parallel, large blue circles are visible in Northern Croatia and Western Macedonia where large storage capacities exist. Note that the Ebro region also has several blue dots. More difficult to see, region Galati has small circles whose color ranges from white to pale red.

Table 1-1 List of the eight regions studied within the framework of STRATEGY CCUS project and their denominations; the column titled 'available storage capacity' reflects the forecast availability of the storage considered for the project in 2050 (the colour is related to the colour scale in Figure 1)

Country	Region	Available Storage Capacity
Croatia	Northern Croatia	Yes
France	Paris Basin	Yes
	Rhône Valley	No
Greece	West Macedonia	Yes
Poland	Upper Silesia	No
Portugal	Lusitanian Basin	Yes
Romania	Galati	Yes
Spain	Ebro Basin	Yes

Reading this map (Figure 1), we can easily identify that the Upper Silesia has limited storage capacities as well as Rhone Valley. In fact, in the case of the Rhone Valley, it is impossible to store all the CO_2 captured locally. Moreover, in this regional scenario part of the CO_2 is already transported to the Paris basin at the storage site appearing in red. For these two regions with large industrial complexes composed of highly emitting industries such as steel, cement or coal-fired power stations (in Upper Silesia), this result is not surprising.

In the case of Galati (Romania), we observe that the size of the circles is modest compared to that of the other regional storage sites, reflecting the fact that the storages considered are small. Eastern Romania actually has many other storage sites available near the emitters. The region is historically an oil producing region. Therefore, the calculated filling rate, based on the storage capacities considered in the regional scenario, does not reflect the real regional situation, and the Galati has

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sufficient storage space referring to the WP2 database (Mesquita & Carneiro, 2020). Moreover, as Galati is geographically distant to the east compared to the other regions considered in the project, after discussion with the Romanian team, we agreed not to include this region in the trans-national analyses.

For the Lusitanian region, the situation is quite similar. It appears from the Figure 1 that the regional storage capacity is sufficient for the regional needs. This time the region is far to the west side compared to the other regions considered in the project. After discussion with the Portuguese team, we agreed not to include this region in the cross-country analyses.

Figure 1: **Storage capacities of the eight regions as part of STRATEGY CCUS Project; the size of the circles is function of the storage capacity, and the color reflects the forecast filling rate at 2050 (according to the color scale on the right)**

1.2.2 Regions where large storage facilities are available

The Figure 2 shows for the different regions the available storages already identified and connected in the regional scenarios. The main available storages are in Northern Croatia, Western Macedonia (Greece), the Ebro basin (Spain). The two largest storages have codes HR.SU.005 and GR.SU.001 and respective capacities of 1940 Mt and 1015 Mt. These are two deep saline aquifers.

According to the regional scenarios (Coussy et al., 2022), the eight regions should store approximately 350 Mt of CO_2 between 2022 and 2050. This quantity corresponds to an average annual storage rate of 12.5 Mt/year. If we use this average rate to translate the available storage capacities of the reservoirs mentioned above into an equivalent number of years of storage, it appears that we have storage capacities equivalent to several decades (

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It should be noted, however, that the storage capacities in Northern Croatia and Western Macedonia have been derived from results reported in the literature. They should be validated against technical studies. This point will be discussed later.

Table 1-2). This result is very interesting and very encouraging, showing that the storage sites already included in the regional scenarios have significant and available capacities allowing them to be considered as storage sites for the transnational scenarios.

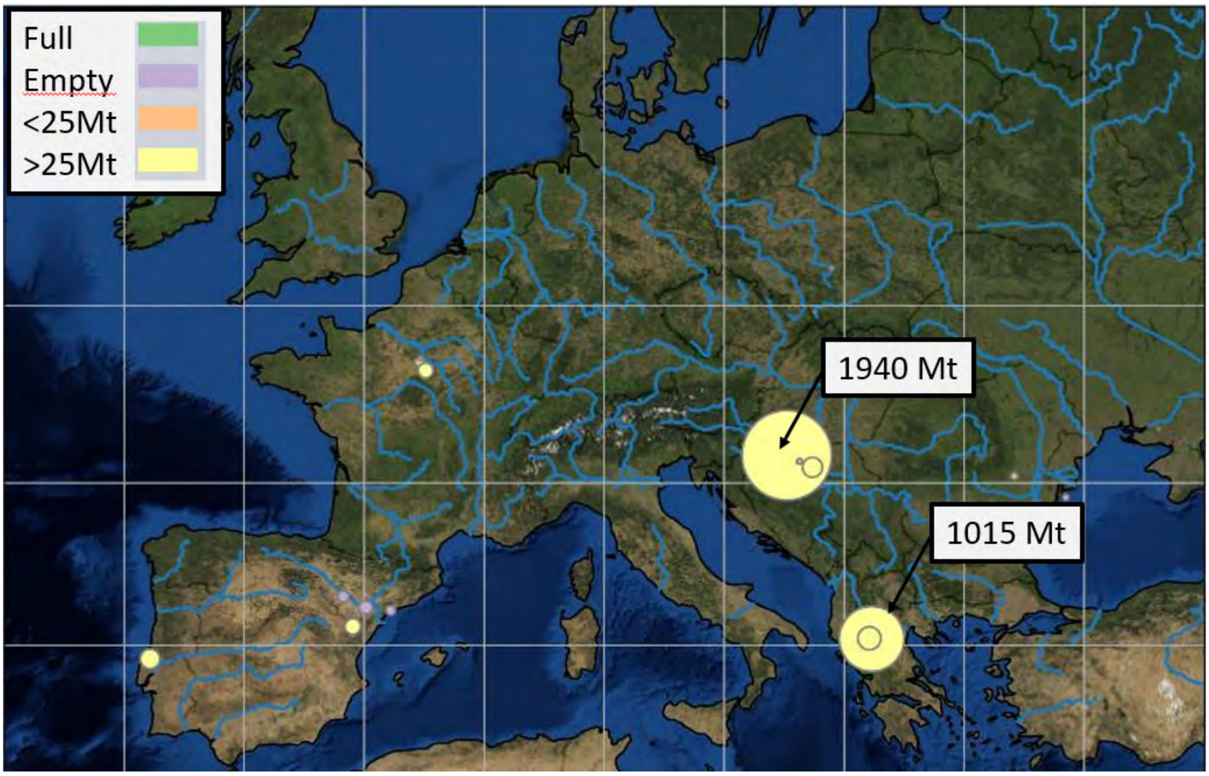

Figure 2: **Regions where large storage facilities are available as part of Strategy CCUS Project**

It should be noted, however, that the storage capacities in Northern Croatia and Western Macedonia have been derived from results reported in the literature. They should be validated against technical studies. This point will be discussed later.

Table 1-2 Equivalent years of storage in regions where large storage resources are available as part of STRATEGY CCUS project. The equivalence timing in years is the period to fill in storage resources with estimated quantity of captured CO_2 within the eight regions

Regions	Equivalent years of storage
Northern Croatia	160 years
West Macedonia	85 years
Ebro Basin	16 years
Lusitanian Basin	12 years

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1.3 Possible European CO_2 transport routes

1.3.1 Transport network resulting from the regional studies

Figure 3 presents an overview of the regional transport networks resulting from the regional scenarios (Coussy et al., 2022). It is clear that except for the Rhone Valley scenario, which transports CO_2 over long distances to the Paris basin, each region has a tight network which is relatively limited to the close vicinity of the emitters and storage facilities. Transport is mainly operated by pipelines but also possibly by maritime transport and to a lesser extent by train.

Figure 3: Regional transport network of the eight regional scenarios; Thickness of the line is proportional to the amount of transported CO_2

This configuration unfortunately leads to a set of regional networks isolated from each other without any interconnection highlighted during the regional studies, except once again, the interconnection between the Rhone Valley scenario and the Paris Basin scenario. Nevertheless, we can note that three regions have connections with the Mediterranean Sea, the Rhone Valley region, the Ebro region, and Macedonia through major ports: Marseille, Barcelona, Tarragona and Thessaloniki.

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1.3.2 Overview of the Trans-European Transport Network

Possible CO_2 transport routes here described are those corresponding to the EU Trans-European Transport Network (TEN-T). The TEN-T[1]:

- Aims at building an effective, EU-wide and multimodal transport network across the EU.
- Comprises railways, inland waterways, short sea shipping routes and roads linked to cities, maritime and inland ports.

Figure 4 displays a general view of the European rail network, highlighting the interconnections with rivers and seaports. The green lines represent the railways and the anchors in a blue circle the ports.

Solid green lines doubled with a hatched green line indicate the existence of railways that need to be improved. Figure 4 clearly shows that the rail network is more reliable in Western Europe than in Central or Eastern Europe. Thus, we note a good connection by train between the ports of Tarragona, Barcelona and Marseille.

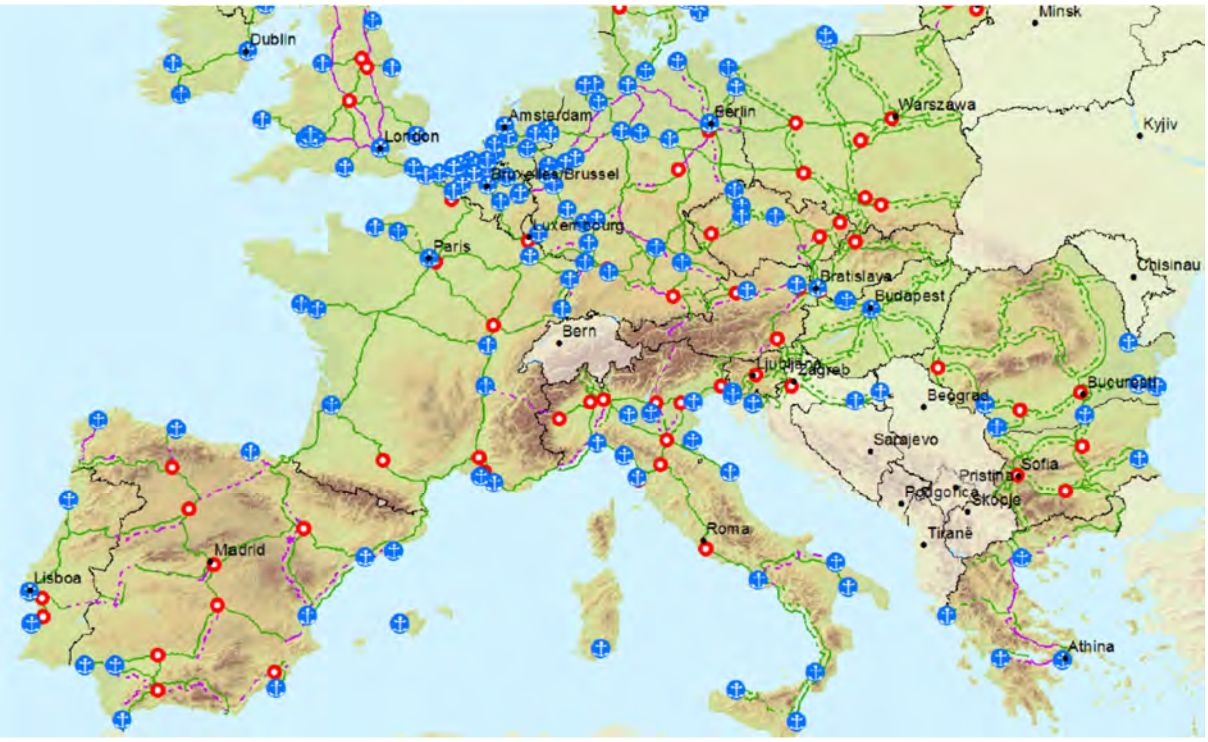

Figure 4: TEN-T for railway network connecting major ports; the green lines represent the railways and the anchors in a blue circle the ports. The red circles are the Rail-Road-Terminals.

[1] TEN-T Maps: https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/site/en/maps.html

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On Figure 5 is displayed a European map of river waterways and also locations of the main rivers- and seaports. Appear there without surprise the major Mediterranean ports of Tarragona, Barcelona, Marseille, and Thessaloniki involved in the regional networks of the Ebro region, the Rhone valley, and Western Macedonia. It is worth mentioning that in Central Europe, the Danube River connects the port of Bratislava (Slovakia) to the port of Osijek (Croatia). The latter being integrated into the transport network of the Croatian scenario.

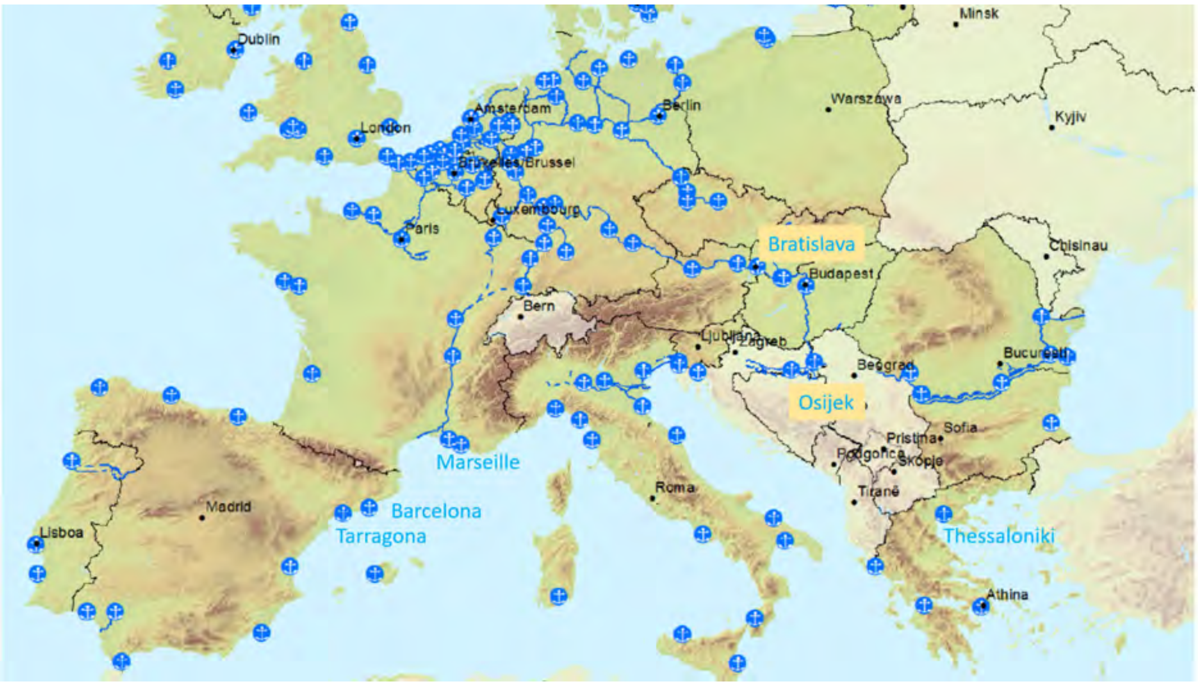

Figure 5: TEN-T for shipping; the anchors in a blue circle represent either the fluvial or maritime ports; The continuous blue lines the inland water ways.

1.3.3 Geographical considerations

In our transnational scenarios for Southern Europe, the Mediterranean Sea plays an important role for transport, making it possible to connect the Rhone Valley region (lacking storage) with the regions of Ebro and Western Macedonia (offering large storage capacities).

For Central Europe, we have seen that connections would be possible by river between Bratislava and Osijek. It remains to connect Bratislava with Upper Silesia. The Figure 6 simply presents the geography of Central Europe. The Pannonian basin occupies a central position, and the Danube crosses it, flowing from west to east. These two regions Upper Silesia and Northern Croatia are separated by the Pannonian basin which is delimited in the north by the Carpathian ridge which represents the main geographical obstacle to be overcome to connect the two regions.

According to Figure 4, railway lines exist between Upper Silesia and Bratislava, although these need to be improved. According to Figure 5, a tributary of the Danube joining the Danube at Komarno downstream from Bratislava, provides a waterway to the foot of the Carpathians at Zilina. Figure 7 shows this region in more detail.

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Figure 6: Geographic features of central Europe.

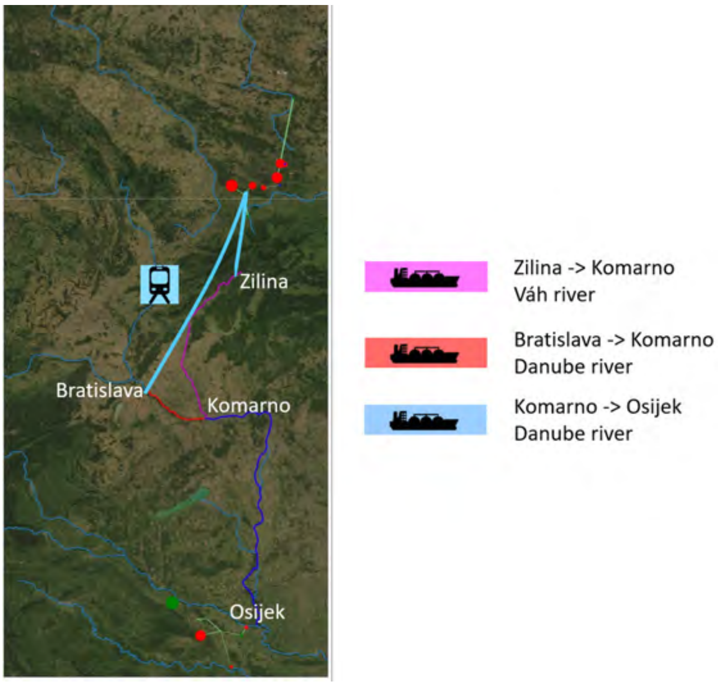

Figure 7: Focus on Central Europe and the waterways linking Upper Silesia and Northern Croatia.

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1.4 Proposed transnational scenarios

Based on **the analysis of the storage capacities** considered for the regional scenarios, we conclude that:

- The two regions of Upper Silesia and Rhône Valley need external storages,
- The two regions of Croatia and West Macedonia, and to a lesser extent the Ebro Basin have large available storage capacities.

Based on **the analysis of the transport network and geographical considerations**, we find out that :

- The Mediterranean Sea makes it possible to connect three regions studied in the project, the Marseille region (France), the Ebro region (in Spain), and Western Macedonia (Greece)
- The distance as the crow flies between Upper Silesia (located in the extreme south of Poland) and northern Croatia is around 500 km. These two regions are separated by the Pannonian basin which is bounded on the north by the Carpathian ridge which represents the main geographical obstacle to be overcome to connect the two regions.

From the elements cited above, we propose to study three transnational scenarios, the main characteristics of which we recall below and in the Table 1-3. Each transnational scenario will be presented in detail in a following dedicated section of the report also recalling the main characteristics of regional scenarios included in the transnational scenario.

1. **Upper Silesia – Northern Croatia transnational scenario:**
    - Upper Silesia has a very dense heavy industry network, unfortunately storage capacities are limited.
    - Northern Croatia, on the other hand, has large storage capacities and a dense network of pipelines.
    - Poland certainly has storage resources in the north, but they have not been considered in this study.
    - It is interesting to note that the distance “as the crow flies” between Silesia and the Baltic Sea is comparable to the distance between Silesia and Northern Croatia, e.g. about 500 km.
2. **Rhone Valley – Ebro transnational scenario:**
    - The Rhone Valley region has a dense network of heavy industries organized around the port of Marseille.
    - The region has limited storage capacity, which cannot accommodate the quantity of CO_2 to be captured. In the national scenario, CO_2 is sent to the Paris region by pipeline and train.
    - The Ebro region has several industrial clusters located on the coast.
    - The region also has good storage capacities.
    - The regional scenario has a dense transport network with port interconnections.
    - Sea going vessels from Marseille to *Golfo de Sant Jordi* (Tarragona region).
3. **Rhone Valley – Ebro – West Macedonia scenario:**
    - West Macedonia region: an efficient pipeline network linking the large storage facilities in the west with the port of Thessaloniki.

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- Sea going vessels from Marseille to *Golfo de Sant Jordi* (Tarragona region).
- Sea going vessels from *Golfo de Sant Jordi* (Tarragona region) to Thessaloniki.

Table 1-3 Proposed transnational scenarios

Regions under pressure	**Regions with available storages**	**Rough CO_2 amounts to be transported**	**Potential connections**	**Rough distance**
Upper Silesia	Northern Croatia	2 Mt/y	River, train, pipeline	500 < d < 700 km
Rhône Valley	Ebro Basin	1.5 Mt/y	Sea-going vessels, train	500 km
Rhône Valley + Ebro Basin	West Macedonia	7,5 Mt/y	Sea-going vessels	2 600 km

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2 Upper Silesia – Northern Croatia scenario

2.1 Context

2.1.1 Brief presentation of the Upper Silesia scenario

The Polish long-term scenario assumes that carbon dioxide is captured from seven emitters (large power and heating plants) and underground storage is operated in two storage units (DSA). It assumes also that CO_2 is going to be utilized in two methanol plants (Figure 8). For the aim of reducing the cost of infrastructure, two hubs were included in this scenario.

Due to large volumes of CO_2, the scenario assumes transport of CO_2 mainly via pipelines – seven pipelines were included. Total length of the pipelines network is 170 km and diameters vary in the range 114-227 mm. One rail connection for one smaller emitter and distance c.a. 20 km was considered as well.

From the total estimated captured CO_2 in the scenario equal to 106 Mt, 91.4 Mt is to be stored in two DSAs and 13.2 Mt used for methanol production.

Total discounted CAPEX of the the Upper Silesia long-term scenario was estimated at 1,289.8 M€, including:

- ✓ Capture: 990.7 M€,
- ✓ 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 ton of CO_2 avoided, the total discounted CAPEX and OPEX are 25.39 €/ton CO_2, 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 compliance costs were calculated to be 16,033.3 M€. The total cost of the CCUS scenario is thus (2,344.2 + 16,033.3=) 18,377.5 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 22,184.6 M€. **This means that the scenario without CCUS is more expensive than the scenario with CCUS by 3,807.0 M€**. Key Performance Indicators (KPIs) for the long-term scenario for Upper Silesia are presented in Figure 9**Erreur ! Source du renvoi introuvable.**.

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Figure 8 : map of the Upper Silesia CCUS scenario

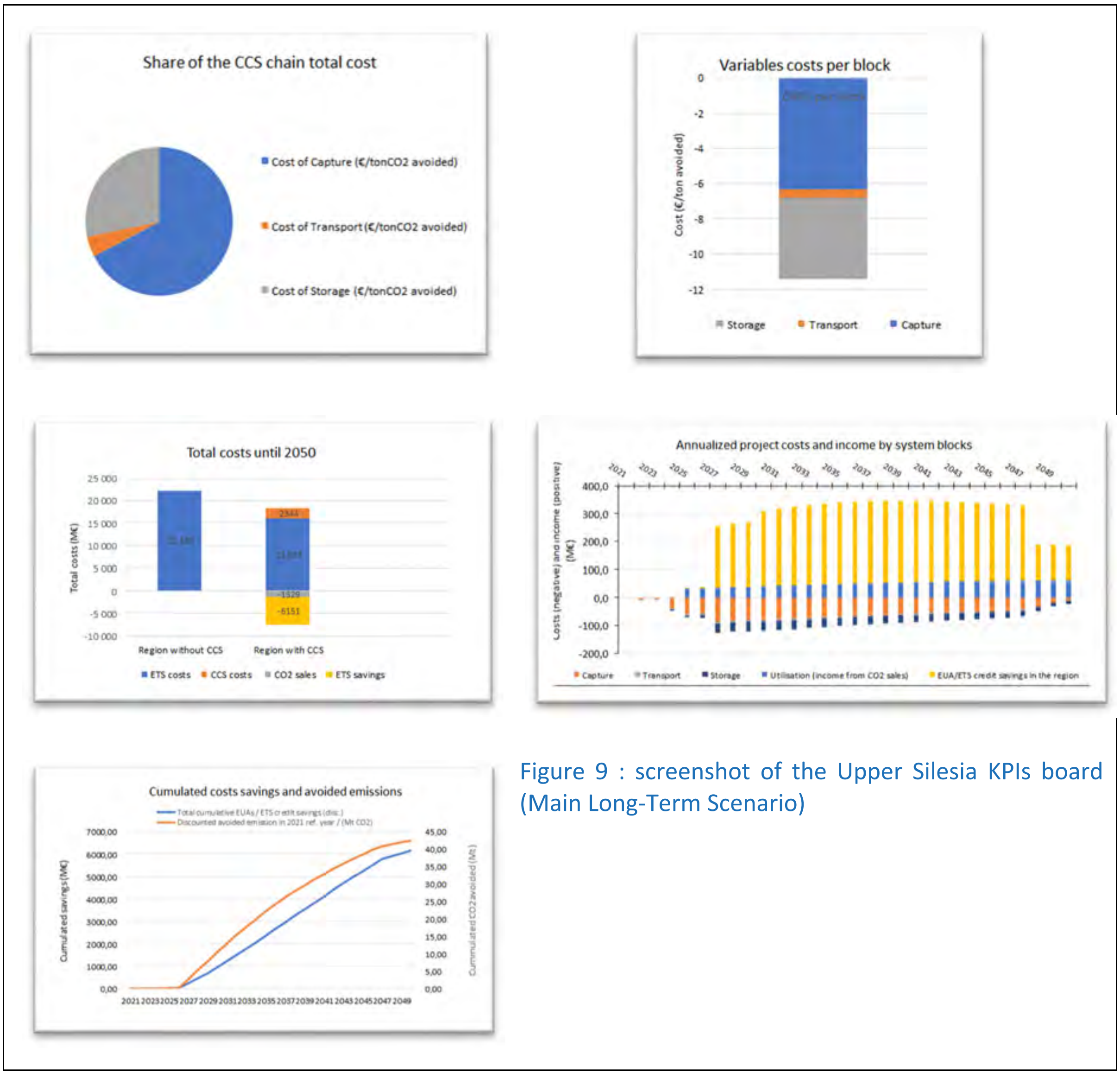

Figure 9 : screenshot of the Upper Silesia KPIs board (Main Long-Term Scenario)

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2.1.2 Brief presentation of the Northern Croatia scenario

In the Croatian Main Long-Term Scenario three emitters and three storage units (2 depleted hydrocarbon fields and one aquifer) are included. One of the two hydrocarbon fields will be subjected to EOR CO_2 utilization scheme in one part of the observed period. From 29.8 Mt of CO_2 captured in total, 1.1 Mt are used for enhanced oil recovery and 27.1 Mt are stored. All CO_2 transport is foreseen to be via 7 pipelines with the overall length of 148 km, with most of the pipelines carrying the captured CO_2 to hubs, and one of them directly to one of the storage units (Figure 10 and Figure 11).

Total discounted CAPEX of the the Northern Croatia long-term scenario was estimated at 301.7 M€, including:

- ✓ Capture: 149.5 M€,
- ✓ Transport: 26.6 M€,
- ✓ Storage: 125.6 M€.

The total discounted OPEX for the analysed period amount to 468.8 M€, including:

- ✓ Capture: 155.3 M€,
- ✓ Transport: 15.7 M€,
- ✓ Storage: 297.7 M€.

Therefore, the **total discounted CAPEX and OPEX amount to 770.4 M€.**

Per ton of CO_2 avoided, the total discounted CAPEX and OPEX are found to be 27 €/ton CO_2, including:

- ✓ Capture: 10 €/ton CO_2,
- ✓ Transport: 3 €/ton CO_2,
- ✓ Storage: 14 €/ton CO_2.

In the scenario with CCUS, the discounted ETS compliance costs were calculated at 241 M€. The total cost of the CCUS scenario is thus 1,011 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 1,638 M€. **This means that the scenario without CCUS is more expensive than the scenario with CCUS by 628 M€**. Key Performance Indicators (KPIs) for the long-term scenario for Northern Croatia are presented in Figure 11

2.1.3 Potential benefits to mutualize facilities between Upper Silesia and Northern Croatia

- Upper Silesia has a very dense heavy industry fabric, unfortunately storage capacities are limited
- Northern Croatia, on the other hand, has large storage capacities and a dense network of pipelines
- Poland certainly has storage facilities in the north, but they have not been considered in this study.
- It is interesting to note that the distance as the "crow flies" between Silesia and the Baltic Sea is comparable to the distance between Silesia and Northern Croatia, about 500 km

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2.2 Proposed scenario

The CO_2 storage potential of the Upper Silesia region is insufficient considering the large amounts of CO_2 emitted, mainly due to the location of numerous power plants, combined heat and power plants and heavy industry (metallurgy and coking) in the region. Therefore, there is a need to access potential storage sites located outside the region. The most reasonable is to consider storage sites located in other regions of Poland, and then to identify possible storage destinations outside of Poland. However, the work methodology adopted during the implementation of Task 5.3 assumes the use of data collected during the earlier phase of the project under WP2. Hence, due to the lack of characteristics of potential storage sites in Poland in the database resulting from the work of WP2, the KPI calculations with the use of the excel tool were performed only for the transnational storage variant assuming transport of CO_2 from Upper Silesia to Northern Croatia.

The transnational scenario takes into account the possibility of CO_2 captured and transmission to Croatia from two Polish power plants: the new 'New Jaworzno' unit with a capacity of 910 MW, operating from 2021, and the coal-fired IGCC Łaziska power plant with a power of approximately 250 MW, planned for construction.

Various modes of transport were initially considered, namely (1) rail transport, (2) combined rail transport to the port of Bratislava with subsequent water transport along the Danube River to the Osijek storage site and (3) transport via pipeline.

According to the tables of river transport on the Danube[2], vessels with a capacity of 2000 tons can be considered between Bratislava and Osijek, and the transport time between Bratislava and Osijek is about 32 hours. The quantity of CO_2 to be transported is 5.3 Mt/year, which would involve the circulation of 30 boats between the two ports. In other words, a boat should be loaded every 3h20. This logistics seems to us to be difficult to achieve. These first calculations are indicative, and a study on the design of dedicated vessels with an optimized size could be considered.

A boat with a capacity of 2000t corresponds to a full train made up of more than 30 wagons, otherwise you must imagine that every day a minimum of 30 trains would have to run between Upper Silesia and Bratislava! The logistics of this first section of the journey seem prohibitive for the project.

Finally, **considering large capacity of the storage site the DSA Drava was chosen for storage and due to large amount of gas transported, transport via pipeline is the only suitable option in the transnational scenario**. The route of the pipeline was optimized to minimize elevation changes and avoid protected areas or large cities. After modelling, the calculated pipeline length from Upper Silesia to Northern Croatia equals to 655 km with the calculated diameter 515 mm.

The pipeline route runs through several countries: Poland, the Czech Republic, Slovakia, Hungary, and Croatia, which raises legal problems. Further analysis of such a scenario would require an assessment

[2] http://ines-danube.info/goto.php?target=file_1545_download&client_id=viailias4

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of the European as well as the domestic laws of all these countries in terms of the possibility of international transport of carbon dioxide.

In the proposed transnational scenario, the following emitters and storages are foreseen:

Emitters	Storages
Elektrociepłownia Tychy (Zakład Wytwarzania Tychy Tauron Ciepło Sp. z o.o.) - PL	DSA Drava & Onshore - HR
Zakład Wytwarzania Nowa - PL	DSA Osijek & Onshore - HR
Nowe Jaworzno - PL	Benicanci & Onshore - HR
Nowy Rybnik - PL	Boksic & Onshore - HR
Elektrownia Koksowni Przyjaźń - PL	Upper Silesian Coal Basin (USCB) & Onshore - PL
ELEKTROCIEPŁOWNIA KOKSOWNI PRZYJAŹŃ - PL	Jurassic Częstochowa District (JCD) & Onshore - PL
Našicecement d.d. - HR	
TE-TO OSIJEK - HR	
Kogeneracijsko postrojenje Viridas Biomass - HR	
IGCC Łaziska - PL	

Three utilization scenarios were defined (1) EOR in Croatia and (2) METHANOL in Poland), and the excess of the emissions from Nowe Jaworzno and IGCC Łaziska is to be transported to DSA Drava via one pipeline of around 655 km with one booster station.

The storage sites in Poland are retained and are connected to the Polish CO_2 transport network in the transnational scenario. Within these storages, space is free up by transporting CO_2 to Croatia. So we chose to increase the catchment in Poland with the aim of filling the free space. By proceeding in this way, the quantity of CO_2 captured for the transnational scenario reaches 251 Mt, a remarkable value which can be compared to the 350 Mt of the eight regions (Coussy et al., 2022).

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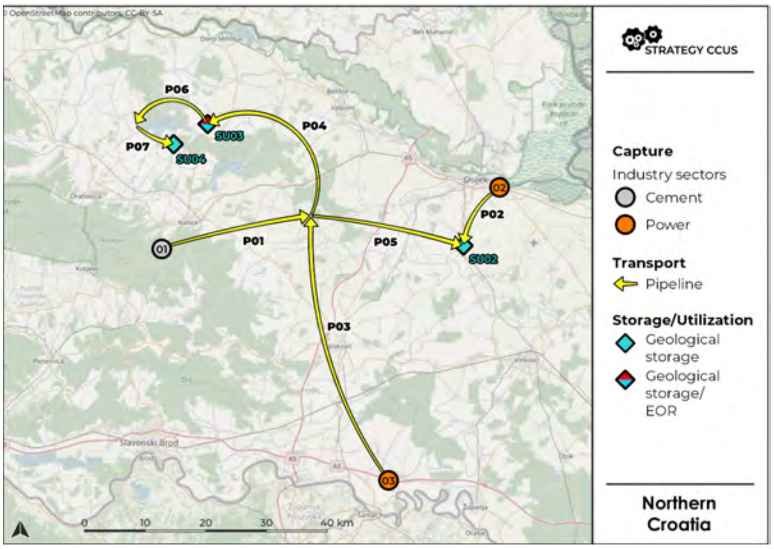
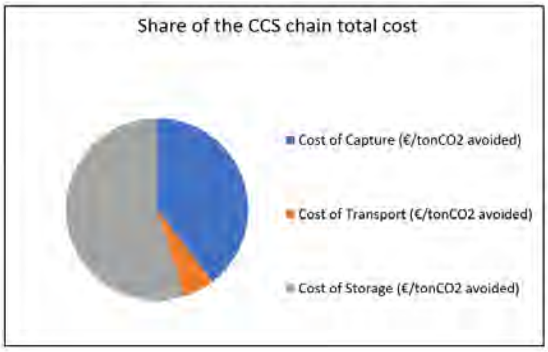
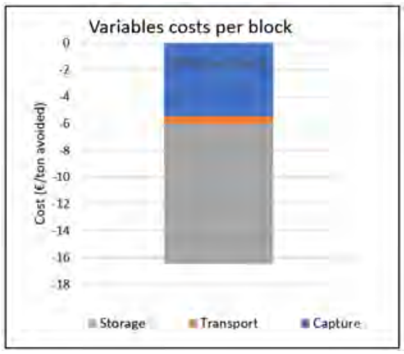
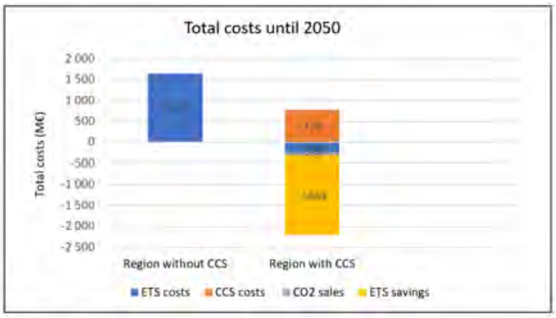
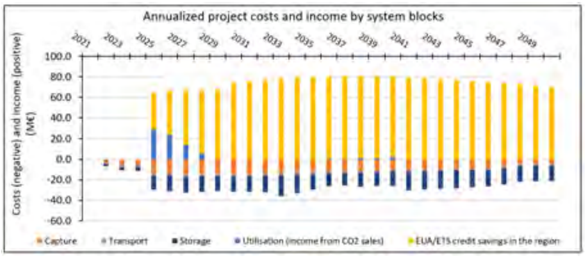


Figure 10 : map of the Northern Croatian CCUS scenario









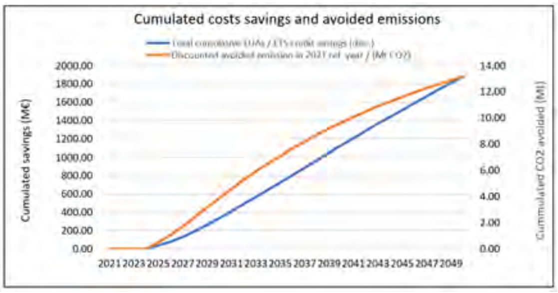


Figure 11 : screenshot of the Northern Croatia KPIs board (Main Long-Term Scenario)

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2.3 Analysis of the transnational scenario

Total discounted CAPEX of the transnational scenario was estimated at 2,931.7 M€, including:

- ✓ Capture: 1,648.0 M€,
- ✓ Transport: 740.0 M€,
- ✓ Storage: 543.7 M€.

The total discounted OPEX for the analyzed period amount to 2,247.5. M€, including:

- ✓ Capture: 1,076.1 M€,
- ✓ Transport: 405.4 M€,
- ✓ Storage: 766.0 M€.

Therefore, the **total discounted CAPEX and OPEX amount to 5,179.3 M€.**

Per ton of CO_2 avoided, the total discounted CAPEX and OPEX are 22.08 €/ton CO_2, including:

- ✓ Capture: 11.61 €/ton CO_2,
- ✓ Transport: 4.88 €/ton CO_2,
- ✓ Storage: 5.58 €/ton CO_2.

In the scenario with CCUS, the discounted ETS compliance costs were calculated at 8,191.5 M€. The total cost of the CCUS scenario is thus 13,370.7 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 23,823.4 M€. **This means that the scenario without CCUS is more expensive than the scenario with CCUS by 10,453.0 M€.** The calculation results are presented graphically in the Figure 12.

The most obvious benefit of this scenario compared to national Croatian scenario is the lower breakeven price. The biggest challenge was to find the optimal route for the pipeline between the two countries. Main uncertainties regarding the results come from economic analysis input parameters such as expectations of future prices and their trends.

Moreover, considering the lack of sufficient prospects for carbon dioxide storage in the Upper Silesia region, as well as the key role of power plants located in this region for the stability of the Polish power system and the country's energy security, the possibility of storing CO_2 outside the region is associated with environmental benefits and an increased potential to reduce the impact Polish energy industry on the climate.

Taking into account the total discounted CAPEX and OPEX calculated per ton of CO_2 avoided, the transnational scenario is economically more efficient: 22.08 €/ton CO_2 avoided by the transnational scenario and 25.39 €/ton CO_2 avoided by the Upper Silesia long-term scenario. The transnational scenario generates 10,453 M€ savings in relation to the scenario without CCUS, mainly due to an efficient capture on the power plant facilities. In Upper Silesia long-term scenario, these savings are lower and amount to 3,807 M€.

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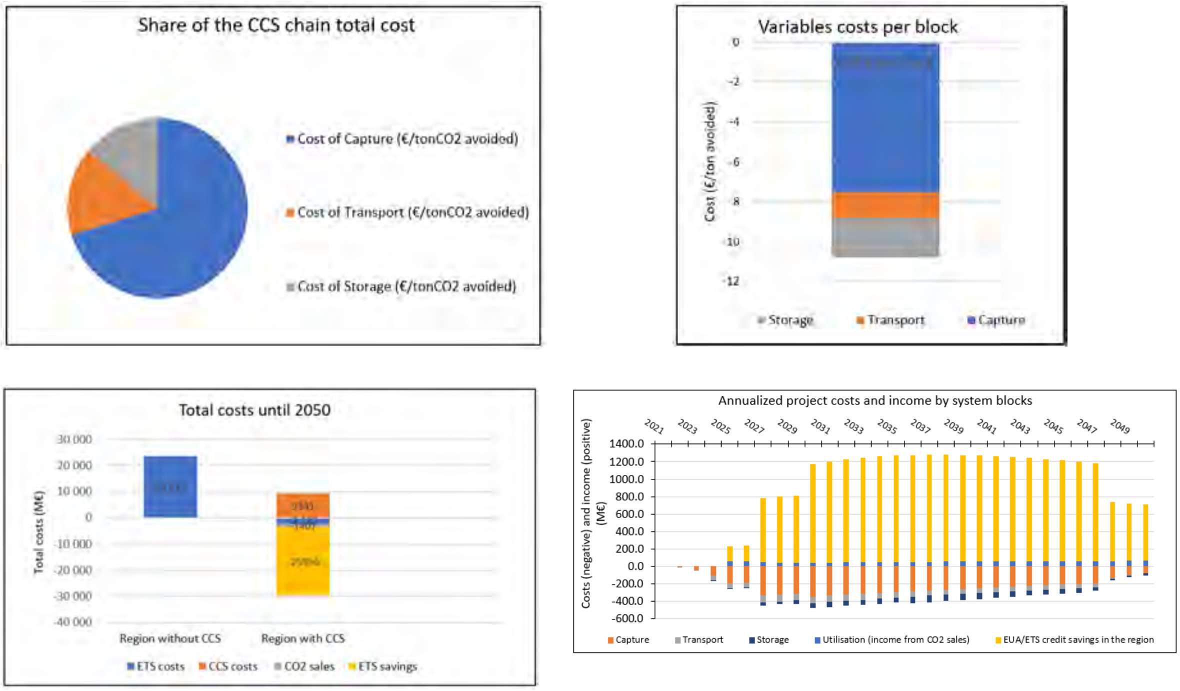

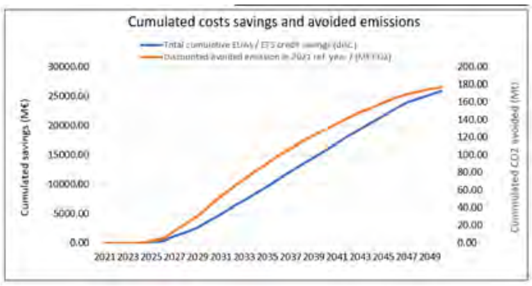

Figure 12 : screenshot of the KPIs board of the transnational scenario for Central Europe

Summary of the results of the transnational scenario:

- CO_2 capture: 251 Mt
    - x2 in comparison to initial regional scenarios
- CO_2 transported to North Croatia: 108 Mt
- Transnational pipeline cost: 630 M€ (discounted)
- The pipeline route runs through several countries: Poland, the Czech Republic, Slovakia, Hungary and Croatia
    - Further analysis of such a scenario would require an assessment of the European as well as the domestic law of all these countries in terms of the possibility of international transport of carbon dioxide.

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3 Rhône Valley – Ebro Basin scenario

3.1 Context

3.1.1 Brief presentation of the Rhône Valley scenario

Six industrial sites near Fos-sur-Mer in the Marseille cluster (Table 3-1) are considered for capture in the Long-Term scenario. CO_2 emissions of these 6 sites were 9.3 Mt in 2018, out of 18.6 Mt for the entire region.

Table 3-1 Emitters considered for capture in the Rhône Valley Long-Term scenario

Facility name	ArcelorMittal FOS	AIR LIQUIDE HYDROGENE SMR Lavéra	Petroineos Manufacturing France SAS	Kem One Lavéra	LAFARGEHOLCIM CIMENTS - USINE de La Malle	EVERE
Industry sector	Iron & Steel	Hydrogen	Refining	Chemicals	Cement	Energy from waste
2018 Reported emission (Mt/y)	7,46	0,18	1,21	0,07	0,43	0.40
CCU/CCS	CCU	CCS				
Start Year	2026	2030	2030			2040
End Year	2050	2040	2050			2050

Given this CCUS roadmap, 50.5 Mt of CO_2 would be captured (21.1 Mt to be used for ethanol production + 29,4 to be stored) by equipping these sites **over the 2026-2050 period**.

The cost of CCUS chain 41.3 €/tCO2 avoided (Figure 14)

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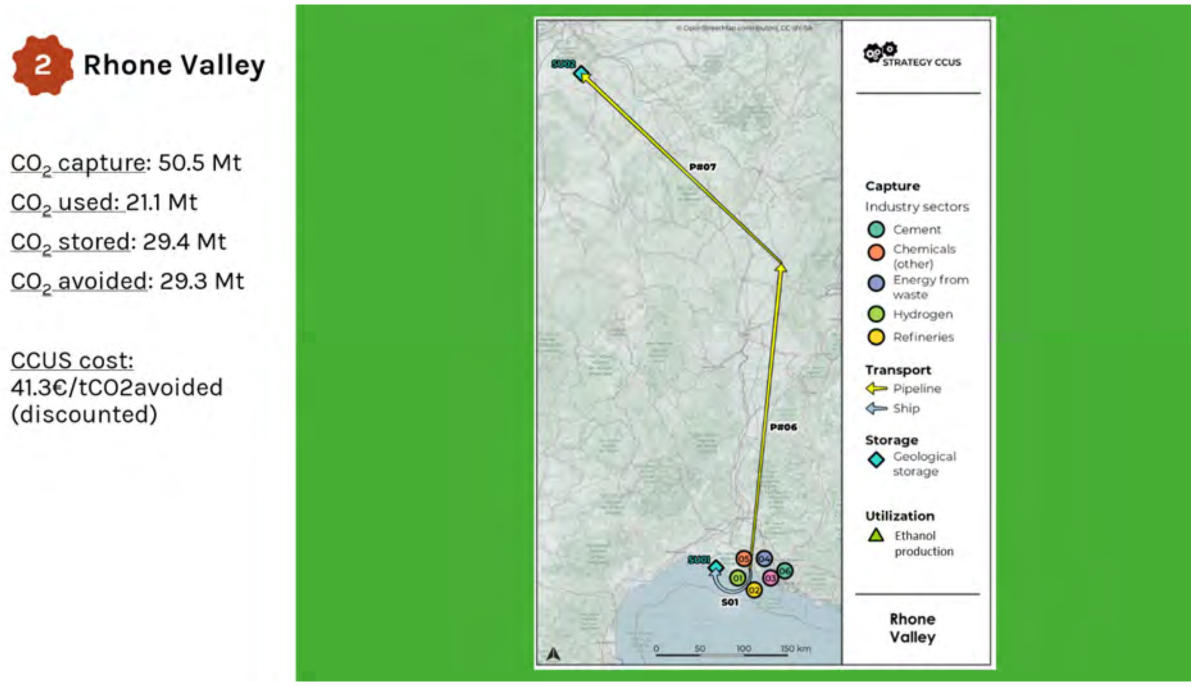

Figure 13: Map of the Rhone Valley regional scenario

Figure 14 : screenshot of the Rhône Valley KPIs charts (Main Long-Term Scenario)

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3.1.2 Brief presentation of the Ebro Basin scenario

The Ebro Basin long term scenario is based on the most extensive regional network that can be established for connecting the different emitters. This scenario considers 14 emitters with a total emission of 9.7 $MtCO_2$ per year (Mt/y, 2017) and mainly around two clusters: Tarragona cluster (Emitters E1, E2, E3, E7, E8, E11 and E13, with 5.76 Mt/y CO_2 (2017) and mainly chemical industry and Barcelona cluster (E4, E5, E6, E9, E12, and E14) with 3.7 Mt/y CO_2 (2017) based on cement industry. Note that a thermal power station located West of the region is too far away to be connected to the two hubs mentioned above. It was decided to keep this plant isolated from the main transport network by connecting it directly by pipeline to the SU05 storage site.

The capture from all of them are between 40% and 50% of total emissions considering the future reduction on CO_2 produced due to the application of other technologies (renewable energy, process efficiency).

About utilization, it is expected that 3 utilizations technologies will be available from 2030 onwards: methanization for biofuels and polymers production considering the interest of the chemical and petrochemical industries in the area; mineralization for the cement industry and CO_2 pure as subproduct also for the chemical industry. In the regional study, we estimated that between 4 and 5% of the captured CO_2 could be used by these different industries.

Figure 15 : Map of the Ebro CCUS scenario with KPIs

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3.1.3 Potential benefits to mutualize facilities between Rhône Valley and Ebro Basin

- The Rhone Valley region has a dense network of heavy industries organized around the port of Marseille.
- The region has limited storage capacity, which cannot accommodate the captured CO_2. In the national scenario, CO_2 is sent to the Paris region by pipeline and train.
- The Ebro region has several industrial centers located on the coast.
- The region also has good storage capacities.
- The regional scenario has a dense transport network with port interconnections.

3.2 Proposed scenario

The emitters considered in the transnational scenario are the same as those considered in the two regional scenarios. The transnational scenario differs only from the regional scenarios from the point of view **of the transport network and the storage sites**. The main changes concerning the Rhone Valley region. Thus, the geological repositories in the Rhone delta and in the Paris basin have been abandoned. The transport of CO_2 from the port of Marseille to these two sites has no longer any reason to exist and is replaced by transport to *Golfo de Sant Jordi* in the Tarragona region.

- From Marseille to Tarragona region
  - 1,45 Mt CO_2 / y to be transported from 2030 to 2050
  - Distance by sea : 430 km
  - Ship capacity : 12 000 tons
  - Number of ships : 1

3.3 Analysis of the transnational scenario

Total discounted CAPEX of the transnational scenario was estimated at 2,106 M€, including:

- ✓ Capture: 1,490 M€,
- ✓ Transport: 448 M€,
- ✓ Storage: 167 M€.

The total discounted OPEX for the analyzed period amount to 5,352 M€, including:

- ✓ Capture: 2,824 M€,
- ✓ Transport: 2,290 M€,
- ✓ Storage: 237 M€.

Therefore, the **total discounted CAPEX and OPEX amount to 7,458 M€.**

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Per ton of CO_2 avoided, the total discounted CAPEX and OPEX are 74 €/ton CO_2, including:

- ✓ Capture: 43 €/ton CO_2,
- ✓ Transport: 27 €/ton CO_2,
- ✓ Storage: 4 €/ton CO_2.

In the scenario with CCUS, the discounted ETS compliance costs were calculated at 29,268 M€. The total cost of the CCUS scenario is thus 36,726 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 36,889 M€. **This means that the scenario without CCUS is more expensive than the scenario with CCUS by 163 M€.** The calculation results are presented graphically in the **Erreur ! Source du renvoi introuvable.**.

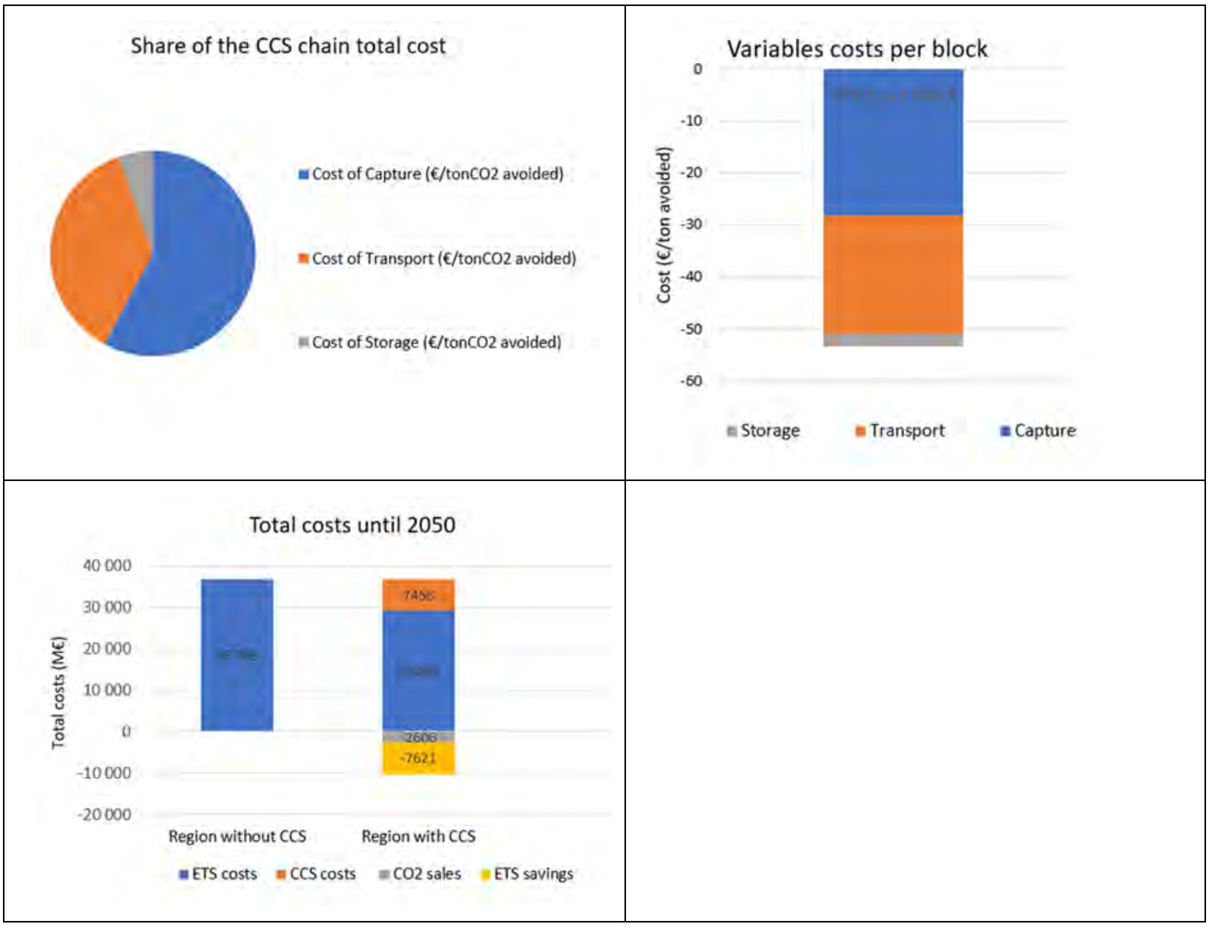

Figure 16: screenshot of the KPIs board of the transnational Rhone Valley – Ebro scenario.

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4 Rhône Valley – Ebro Basin – West Macedonia scenario

4.1 Proposed scenario

The previous scenario showed that it was appropriate to transport the CO_2 captured in the Rhone Valley region (France) to the Ebro region (Spain) by transporting the CO_2 by sea. The Spanish storages are sufficient to accommodate the CO_2 captured in the two regions.

In the first part of the report, we saw that the region of Western Macedonia has very large saline aquifers that can accommodate several hundred million tons of CO_2. When we discussed the possible routes in Southern or Central Europe, the Mediterranean Sea naturally appeared and makes it possible to connect the three regions studied in the project (Rhone Valley, Ebro region and Western Macedonia) via the major ports of Marseille, Tarragona and Thessaloniki. In this paragraph we propose to study an alternative scenario to the previous one and consisting in transporting by boat the CO_2 captured in the Rhone Valley region to the Ebro region, and then transporting the French and Spanish CO_2 by boat to Thessaloniki (Figure 17).

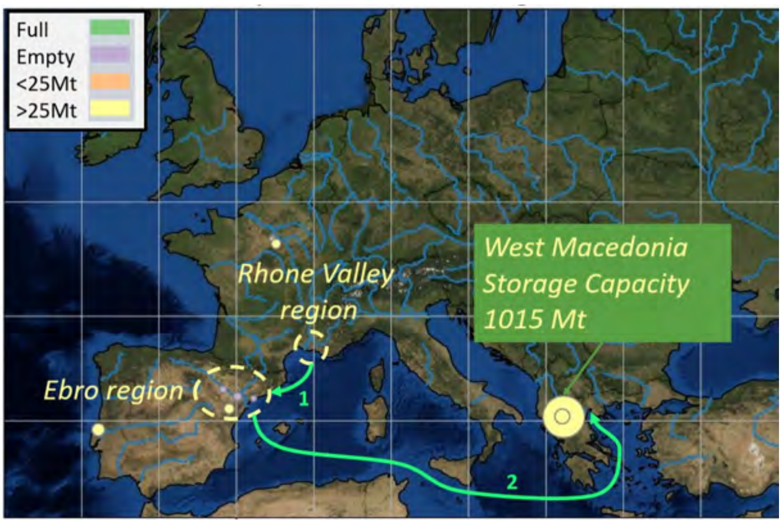

Figure 17: Indicative circuit consisting of (1) transporting the CO2 captured in the Rhone Valley region by boat to the Ebro region, and then (2) transporting the French and Spanish CO2 by boat to Thessaloniki.

Moreover, the Greek transport network imagined for the regional scenario is very interesting since it makes it possible to effectively connect the different sites, cities involved in the scenario by pipelines. Thus, arriving at the extreme East of the network in the port of Thessaloniki, the CO_2 is transported at the extreme West of the network at around 210km (Figure 18).

By collecting CO_2 in the Rhone valley and in the Ebro region, the amount of CO_2 to be transported to Greece annually will reach 7.5 Mt. Of course, even if we use the same pipeline route to transport CO_2 from Thessaloniki to the reservoirs located to the west, it is necessary to increase the size of the infrastructure and build a new pipeline. The new pipeline has a diameter of 1 m.

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Finally, transport by boat requires 7 ships with a capacity of 30 000 kt. The distance between Tarragona and Thessaloniki is around 2700 km, each trip will have a duration of 9 days.

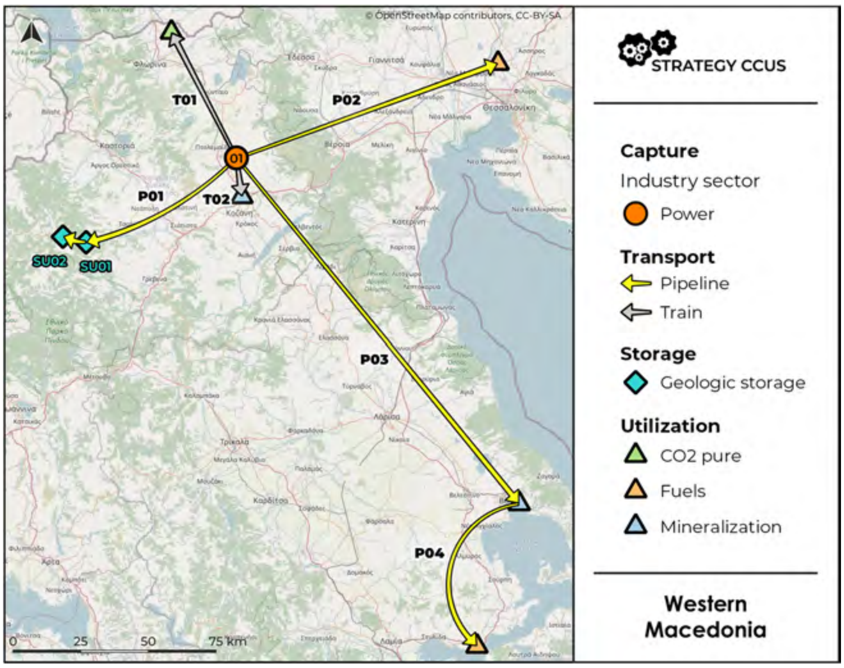

Figure 18: Map of the West Macedonia scenario

4.2 Analysis of the transnational scenario

Total discounted CAPEX of the transnational scenario was estimated at 3,026 M€, including:

- ✓ Capture: 1,641 M€,
- ✓ Transport: 1,234 M€,
- ✓ Storage: 149 M€.

The total discounted OPEX for the analyzed period amount to 6,541 M€, including:

- ✓ Capture: 3,281 M€,
- ✓ Transport: 2,727 M€,
- ✓ Storage: 532,8 M€.

Therefore, the **total discounted CAPEX and OPEX amount to 9,567 M€.**

Per ton of CO_2 avoided, the total discounted CAPEX and OPEX are 71 €/ton CO_2, including:

- ✓ Capture: 36 €/ton CO_2,
- ✓ Transport: 29 €/ton CO_2,
- ✓ Storage: 5 €/ton CO_2.

In the scenario with CCUS, the discounted ETS compliance costs were calculated at 26,989 M€. The total cost of the CCUS scenario is thus 36,556 M€. On the other hand, the discounted ETS costs in the scenario without CCUS were estimated at 36,889 M€. **This means that the scenario with CCUS is less expensive than the scenario without CCUS by 332 M€.** The calculation results are presented graphically in the **Erreur ! Source du renvoi introuvable.**.

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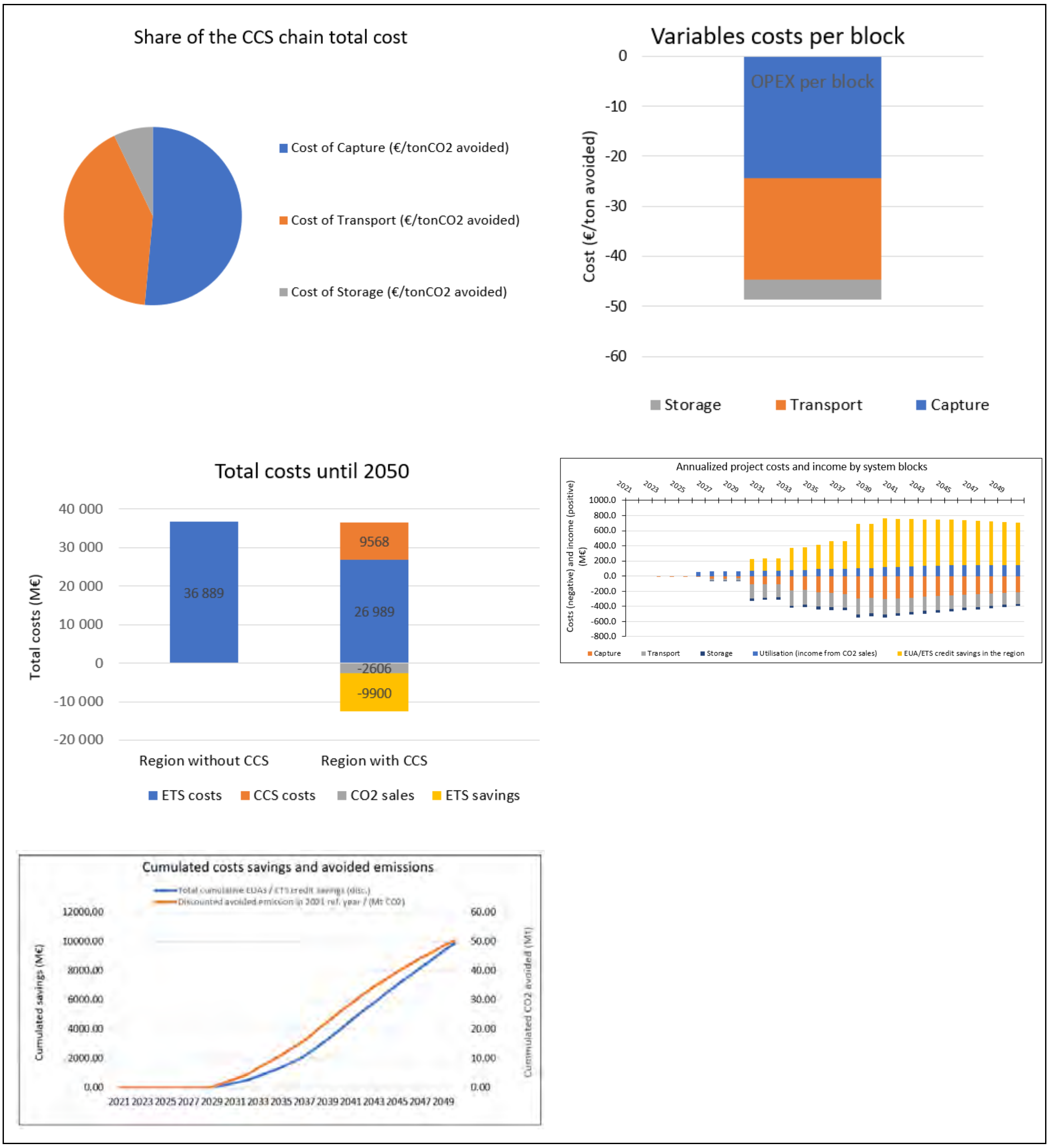

Figure 19: screenshot of the KPIs board of the transnational Rhone Valley – Ebro – West Macedonia scenario.

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5 Conclusion

The regional studies were developed by minimizing the transport of CO_2 by looking for local storage sites and showed that it is possible to store around 350 Mt of CO_2 for the eight regions during the period from 2026 to 2050. By doing so, quite logically the regions with the densest industrial networks fill up their storage sites in 2050. On the other hand, at the end of the regional analysis, the regions have storage sites that could accommodate several dozen years of capture. We have developed transnational scenarios with the aim of relieving regions with limited storage by transporting their CO_2 to large storage sites.

Thus, we propose to transport the CO_2 captured in Upper Silesia to northern Croatia (scenario for Central Europe), the scenario captured in the Rhone valley to the Ebro region, and a variant of this scenario by transporting the CO_2 from the Rhone Valley and the Ebro region to the western Macedonia. Interestingly, transnational scenarios give more flexibility to the CCUS chain by avoiding storage capacity constraints in highly industrialized regions. By lifting the limitation on the storage capacity, it is even possible to increase the quantities of CO_2 captured, thus:

- x2 for the Upper Silesia / Northern Croatia scenario
- +27% for the Rhone Valley / Ebro / Western Macedonia scenario

With these three transnational scenarios, the total quantities of CO_2 captured for 4 regions exceed 400 Mt, i.e., more than for the 8 initial regions.

If, from the point of view of the physical quantities of CO_2 captured and transported, the transnational scenarios are of real interest for the planet, the economic analysis of the transnational scenarios does not make it possible to highlight the effects of scale on the cost of the ton of CO_2 avoided. The costs obtained are comparable to those resulting from the regional analyzes and remain relatively low. Unsurprisingly, transnational scenarios increase transport costs, especially when using ships.

Our scenarios are based on the assumption that storages in saline aquifers have large capacities in Northern Croatia and Western Macedonia. These capacities come from bibliographical studies and must be validated by technical field studies. The dynamic storage calculations carried out with the tool developed in the project provide information on the number of wells to be considered so that the CO_2 injection rate does not generate an overpressure which would cause damage to the cover. The masses of CO_2 stored were obtained from actual parameters of these aquifers provided by the national geological offices. If these initial calculations provide us with a rigorous basis for possible storage over the long term, it will be of primary importance to characterize more precisely the hydrostatic pressure, the fracturing pressure of the cover as well as the heterogeneities of permeability for these saline aquifers in order to have a real estimate of storable volumes.

Finally, transporting CO_2 within Europe between different countries will be possible if European policy and if national policies allow. This last point is beyond the skills brought together to develop the transnational scenarios presented in this report but will have to be clarified to confirm their feasibility.

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

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