Life Cycle Assessment (LCA) in three selected promising regions describing processes involved in CCUS, scaled to a common unit

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Quotation

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Executive summary

The CCUS scenarios developed in the frame of the STRATEGY CCUS project are meant to help decarbonize the economy by cutting direct CO_2 emissions and valorising or storing them. However, the net drop in greenhouse gas (GHG) emissions linked to the implementation of these scenarios needs to be assessed in order to account for potential indirect environmental effects. Therefore, life cycle assessment (LCA) is seen as a most relevant methodology to help identify the net benefits of CCUS and potential points of attention along the value chain, both in terms of GHG emissions and for other relevant environmental aspects.

This deliverable presents the outcomes of the LCA of the CCUS scenarios elaborated in the three most promising regions – namely the Rhône Valley (France), the Ebro basin (Spain) and the Lusitanian basin (Portugal) – selected at an earlier stage of the project. For each region, the set of relevant industrial emitters on which capture is planned is considered. Environmental impacts of the CCUS scenarios are compared to a baseline situation where no CCUS would be implemented on the emitters, i.e. both their direct CO_2 emissions would occur until 2050, and new products supplied through CO_2 utilization pathways would have to be supplied to the market in a conventional way (cf. Figure 1). The related functional unit for each assessment is the capture, transport, use and/or storage of a given amount of CO_2 from concerned emitters during a given year. The climate change impact through GHG emissions is assessed with the IPCC 2013 GWP100 characterization method. Besides, the Cumulative Energy Demand (CED) indicator is also analysed given the potential energy-related concerns of CCUS. First, intermediate years (2020, 2030, 2040 and 2050) are assessed in order to check the trend in net GHG emissions and CED compared to the baseline. Furthermore, the cumulative GHG and CED savings from 2020 to 2050 are also looked at.

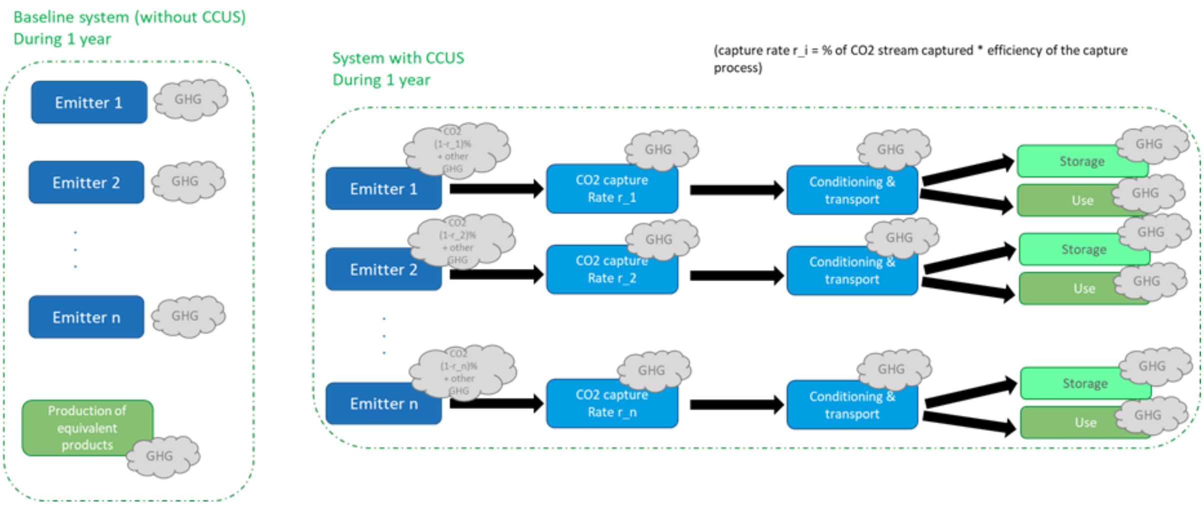

Figure 1: scheme of the baseline and CCUS system perimeters considered for the LCA.

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The modelling is implemented in the Simapro software, using the Ecoinvent LCA database as background. The key parameters – such as capture rates or energy provision for capture – are defined consistently with the techno-economic assessment (TEA) and LCA tasks. Besides, life cycle inventory data for each process block is selected from a wide, initially performed literature review on existing LCA of CCUS-related processes and complemented with adapted Ecoinvent datasets for e.g. CO_2 pipeline transport. Moreover, prospective electricity consumption mixes (required for conditioning, injection and some utilization cases) are modelled for each region based on specific projected scenarios from national institutions.

In the three regions assessed, the implementation of the CCUS scenarios enables net GHG and CED savings compared to the baseline situation from 2020 to 2050. Capture process-related impacts (mainly because of energy provision, both through the upstream impacts of additional fuel supply and the related fuel combustion GHG emissions) are the most critical contributor to generated GHG emissions and significantly to CED, while the conditioning and transport chains globally bear insignificant impact contributions. The storage stage mainly involves a low electricity consumption for injection whose impact is negligible; moreover, the storage of biogenic CO_2 occurring in some regions implies negative emissions which are determinant in the global GHG balance in the Lusitanian basin, while negligible in the Rhône Valley. Finally, the impacts of CO_2 utilization strongly depend on the final use of CO_2 and on the transformation process settings (e.g. renewable power consumption for energy needs). However, the comparison of CCU impacts to those of the substituted conventional products supply and use (occurring in the baseline system) is mostly favourable to CCU, even though no prospective assumptions on potential conventional process evolutions were taken.

In each case, the capture rate and energy consumption for capture, combined with the intensity of yearly CO_2 emissions of the emitters, are found to be the ruling parameters of the GHG reduction efficiency of the CCUS scenarios. The base assumptions in each CCUS scenario (capture rate, energy for capture, conventional products substituted by utilization pathways) play a key role regarding the LCA outcomes in terms of CCUS benefits. Therefore, process integration in the value chain is decisive to optimize net GHG emissions related to CCUS. However, CCUS definitely appears useful to succeed in cutting GHG emissions of the considered regions.

[1] CCUS in Clean Energy Transition, IEA Flagship report, Sept. 2020

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Life Cycle Assessment (LCA) in three selected promising regions describing processes involved in CCUS, scaled to a common unit

1 Introduction

The CCUS scenarios developed in the frame of the STRATEGY CCUS project are meant to help decarbonize the economy by cutting direct CO_2 emissions and valorising or storing them. However, the net drop in greenhouse gas (GHG) emissions induced by the implementation of these scenarios needs to be assessed in order to account for potential indirect environmental effects. Therefore, life cycle assessment (LCA) is seen as a most relevant methodology to help identify the net benefits of CCUS as well as potential points of attention along the value chain, both in terms of GHG emissions and other relevant environmental aspects.

This deliverable presents the outcomes of the LCA of the CCUS scenarios elaborated in the three most promising regions – namely the Rhône Valley (France), the Ebro basin (Spain) and the Lusitanian basin (Portugal) – selected at an earlier stage of the project. For each region, the set of relevant industrial emitters on which capture is planned is considered. Environmental impacts of the CCUS scenarios are compared to a baseline situation where no CCUS would be implemented on the emitters, i.e. both their direct CO_2 emissions would occur until 2050, and new products supplied through CO_2 utilization pathways would have to be supplied to the market in a conventional way. The related functional unit for each assessment is the capture, transport, use and/or storage of a given amount of CO_2 from concerned emitters during a given year. The climate change impact through GHG emissions is assessed with the IPCC 2013 GWP100 characterization method. Besides, the Cumulative Energy Demand (CED) indicator is also analysed given the potential energy-related concerns of CCUS. First, intermediate years (2020, 2030, 2040 and 2050) are assessed in order to check the trend in net GHG emissions and CED compared to the baseline. Furthermore, the cumulative GHG savings from 2020 to 2050 are also looked at.

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2 Goal and scope of the LCA studies

2.1 Goal

The main goal when performing the LCA of the selected regions is to assess the net greenhouse gas (GHG) emission reduction potential of implementing the CCUS scenarios described in D5.2 (Business Model in the eight regions), compared to the case where no CCUS is implemented for the selected emitters (baseline situation). Therefore, assessing each stage of the CCUS chains (capture process, conditioning, transport, storage and utilization) provides a cradle-to-grave picture enabling to account for all potential direct and indirect environmental effects of capturing, using and/or storing CO_2.

LCA results will help identify the key factors (in terms of GHG emission intensity or reduction) of the different life-cycle steps of the CCUS scenarios for the different regions. Besides, results will enable to check the trend in net GHG emissions between 2020 and 2050 and thus the relevance of the CCUS scenarios in terms of global GHG emission reduction for the selected emitters, over the whole CCUS chains (from CO_2 capture to its final storage or transformation into a product).

Finally, other environmental impact categories are further investigated to avoid impact transfer (for instance demonstrating a huge decrease in GHG emissions but missing a consequent rise in energy demand), according to the relevant environmental issues related to CCUS chains.

2.2 Scope

For each region, the related scope of the study is the comparison of the baseline situation (further referred to as "baseline system") with the CCUS scenarios (further called "CCUS system").

Thereby, <u>the baseline system</u> comprises the set of emitters that are considered in the CCUS scenarios, *plus* the conventional production systems for supplying products that are substituted by the CCU-derived products in the CCUS scenarios. Indeed, both systems must be of same perimeter in order for their LCA to be comparable.

<u>The CCUS system</u> includes the whole CCUS chains operated for the considered emitters, until final transformation (via CCU) and storage, as well as the remaining (non-captured, cf. capture rates < 100%) emissions.

The perimeters of both baseline and CCUS systems are depicted in Figure 2.

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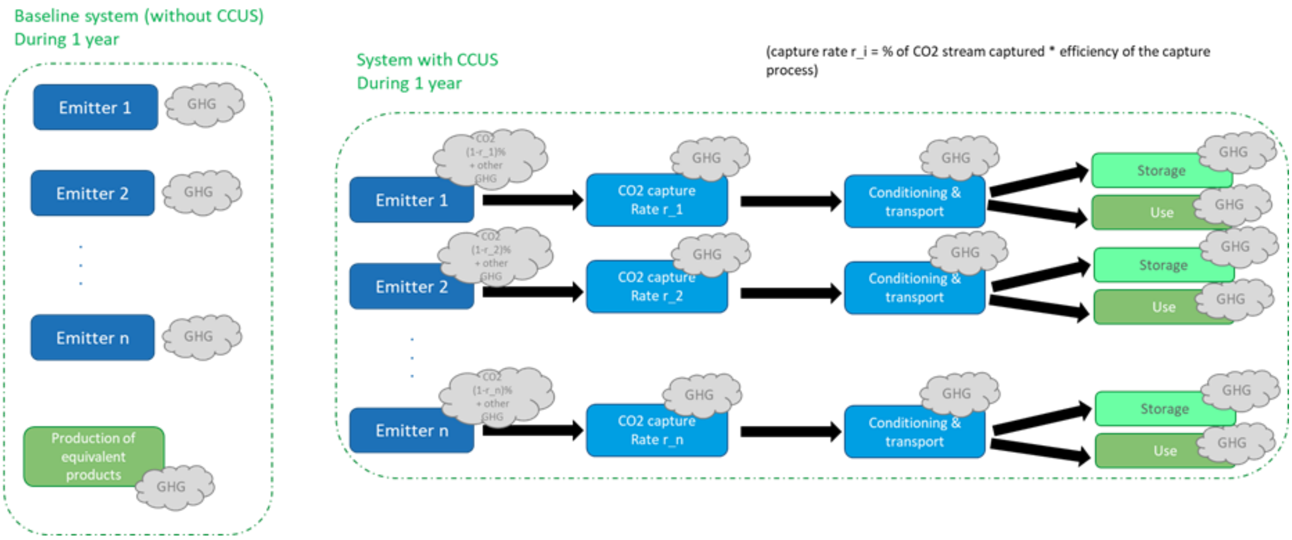

Figure 2: scheme of the baseline and CCUS system perimeters considered for the LCA.

The geographical scope of the study is the region considered (Rhône Valley, FR; Ebro basin, ES; Lusitanian basin, PT). The assessment is first performed for intermediate years from 2020 to 2050, before summing up the cumulative GHG emissions of both systems from 2020 to 2050 to derive the gain of the CCUS system compared to the baseline system.

2.3 System description (regional scenarios)

In this section, a brief description of the regional scenarios is provided. For further details, please refer to the deliverable D5.2 (business case)[1].

2.3.1 Ebro basin (Spain)

Two scenarios for the regional scenarios in the Ebro Basin region have been built. According to Deliverable 5.2 (Report of regional business cases V1.0), first scenario named **Base Scenario for Long Term (BSLT)** of Ebro Basin has been built based on the objective of the most extensive CO_2 network for capturing. This scenario includes the 15 largest emitters in the region, 3 needed storage sites and using the most extensive transportation net (truck, pipeline, and ship). This scenario involves 2 clusters (Tarragona and Barcelona Clusters) and one stand-alone place, starting in 2027.

Considering captured volumes until 2050 and assuming constant the 2017 emissions from each emitter, this BSLT for Ebro Basin could store around 45% of total potential emissions of the emitters

[1] https://www.strategyccus.eu/project-outputs/economics-outputs

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considered and apply CO_2 to other uses at 5% of total captured emissions. Table 1 shows the emitters list and capture rates at BSLT scenario of Ebro Basin.

Table 1: key parameters common to the TEA and LCA of the Ebro basin.

TGN cluster	Industry sector	Reported emission (Mt/y, 2017)	Start Year capture	End Year Capture	Efficiency (% captured)	Annual capture rate (Mt/y)	Tot CO2 captured (Mt)
E#01	Chemicals (other)	1.03	2027	2050	0.4	0.41	9.861
E#02	Chemicals (other)	0.84	2027	2050	0.4	0.34	8.076
E#03	Cement	0.78	2033	2050	0.5	0.39	5.842
E#07	Refinery	2.29	2038	2050	0.5	1.15	14.888
E#08	Hydrogen	0.38	2038	2050	0.5	0.19	2.468
E#11	Power	0.34	2040	2050	0.5	0.17	1.862
E#13	Chemicals (other)	0.11	2045	2050	0.5	0.05	0.319
Total cluster		**5.77**					**43.31**
BCN cluster							
E#04	Cement	1.14	2035	2050	0.5	0.57	9.104
E#05	Cement	1.1	2038	2050	0.5	0.55	7.121
E#06	Cement	0.43	2040	2050	0.5	0.22	2.380
E#09	Power	0.38	2040	2050	0.5	0.19	2.079
E#12	Chemicals (other)	0.21	2040	2050	0.5	0.11	1.180
E#14	Paper and pulp	0.19	2040	2050	0.5	0.09	1.018
E#15	Iron & Steel	0.18	2040	2050	0.25	0.05	0.507
Total cluster		**3.63**					**23.39**
Standalone							
E#10	Power	0.34	2035	2050	0.5	0.17	2.730
Total BSLT		9.74					69.43

As stated in Deliverable 5.2 (Coussy, 2021), in the study zone, there are 4 research lines (mineralization, fertilizers, methanol production and polymers) where some work is being done and

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will be carried out also during the following years. In this sense, in the Base Scenario (BSLT) two possible uses of CO_2 were selected: methanol production, based on the current national strategy for moving off the traditional fossil fuels and the strong demand for methanol, and mineralization, as one of the most promising utilization technologies (and with a higher mature level of this technology) from the cement industry. Assumed participation in the use of CO2 can be seen in Table 2.

Table 2: Participation use of CO2 in the Ebro Basin context

Use		
Product	Participation (%)	Amount (MtCO2)
Methanol	50	2.53
Mineralization	50	2.53

Transport

The network between emitters and storage locations have been designed based on the principles shown in Table 3.

Table 3: Details on transport modes and distances BSLT scenario for the Ebro Basin

Connection type	Number of connections	Distance (km)	CO2 transported (Mt)	Tkm
Pipeline	14.00	420.82	645.4	2.72E+11
Train	4.00	0.09	3.4	3.06E+05
Ship	3.00	105.00	120.5	1.27E+10
Total	21.00	525.91	769.30	

The second scenario for Ebro basin region named "Industry Scenario Long Term" (ILST) is an alternative scenario where selected industries with CCUS technologies were considered in their current strategy: the petrochemical and refinery on Tarragona Cluster, and cement industry, most of them in Barcelona. In that case, capture starting dates and transport network have been adapted to the new situation and considering an initial period of 5 years with low capture and low storage rates and increasing them later. The Tarragona cluster is still based on the petrochemical industries included and the Barcelona cluster, for the cement industry. In this case, only a storage site is considered (Maestrazgo). Table 4 shows the emitters list and captured rate at ISLT scenario of Ebro Basin.

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Table 4: Emitters list and captured rate at ISLT scenario of Ebro Basin

Industry sector	Reported emission (Mt/y, 2017)	Start Year capture	End Year Capture	Efficiency (% captured)	Annual CAPTURE rate (Mt/y)	Tot CO2 captured (Mt)
Chemicals (other)	0.84	2027	2050	0.4	0.34	5.38
Cement	0.78	2033	2050	0.5	0.39	7.01
Cement	1.14	2035	2050	0.5	0.57	9.10
Cement	1.1	2038	2050	0.5	0.55	7.12
Cement	0.43	2040	2050	0.5	0.22	2.38
Refinery	2.29	2038	2050	0.5	1.15	14.89
	6.58					**45.89**

Use

For the ISLT scenario, two CO_2 utilization pathways were selected: methanol production and mineralization, under the conditions defined for this scenario. A total of 2,8 MtCO2 have been considered for use.

Transport

The network between emitters and storage places for ISLT scenario have been designed base on the principles showed in Table 5.

Table 5: Details on transport modes and distances ISLT scenario for the Ebro Basin

Connection type	Number of connections	Distance (Km)	CO2 (Mt)	tkm
Pipeline	9.00	332.31	418.80	1.39E+11
Ship	3.00	130.00	66.70	8.67E+09
Total	12.00	462.31	485.50	

2.3.2 Lusitanian basin (Portugal)

The Lusitanian basin area studied in the STRATEGY CCUS project is in the western central territory of Portugal, covering the NUTS III regions of Coimbra, Leiria, Médio Tejo, Oeste, Lezíria do Tejo and Lisbon Metropolitan Area. In Figure 3, red dots show the location of CO_2 sources with emissions above 80 kt/year in 2018. Major industries in the region include cement, lime, glass, paper and pulp, ceramics, and energy (power and heat production). Pego coal-fired power plant, decommissioned at the end of 2021, was the main emitter in the region and, thus, it is not included in the scenarios.

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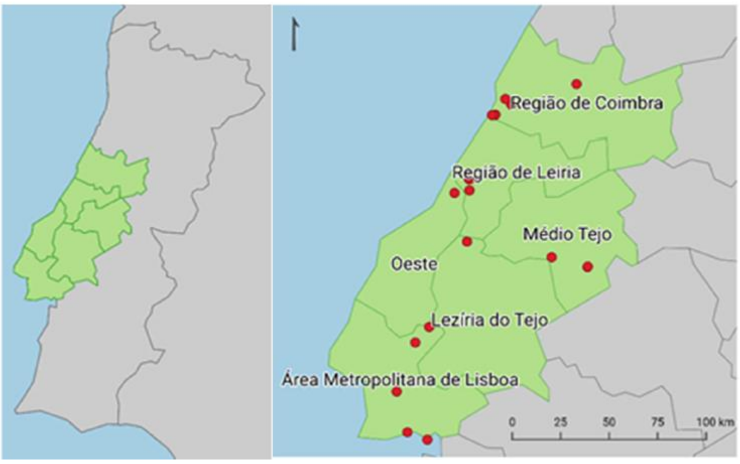

Figure 3: Lusitanian basin area studied in the StrategyCCUS project.

Deep saline aquifers (DSA) are the CO_2 geological storage resources identified in the Lusitanian basin with 17 potential storage units – 4 onshore and 13 offshore. The total onshore storage capacity is approximately 261 Mt CO_2 (central value P50), with an uncertainty interval ranging between 115 Mt CO_2 (P90) and 502 Mt CO_2 (P10), while the offshore units' capacity is approximately 2 900 Mt CO_2 (P50) with an uncertainty interval spanning from 1 500 Mt CO_2 (P90) to 5 400 Mt CO_2 (P10).

A list of all CO_2 emitter facilities in the Lusitanian Basin region is presented in Table 6. It also includes the emissions reported in the year 2018 and the year of start and end of the CO_2 operation for each emitter. In the short and medium-term perspective (2028 to 2035), two carbon capture pilot units are expected around 2028, with a capture efficiency between 6 to 10%: Cement company CIMPOR – Indústria de Cimentos, S.A., Souselas Production Center (E#01/08); and Glass company BA Glass, S.A., Marinha Grande factory (E#02/05).

In the short-term scenario, train is considered for the longer connection distance and pipelines for the shorter connection distances. The scenario considers that 1/3 of the CO_2 captured (37 kt CO_2) would be used in greenhouses in the Oeste NUTS III region, while the rest would be directed to onshore geological storage.

The long term scenario considers that by 2035, the two main cement industries (SECIL - Companhia Geral de Cal e Cimento, S.A, Fábrica SECIL - Outão (E#03) and CIMPOR – Indústria de Cimentos, S.A., Centro de Produção de Alhandra (E#04)) and lime (Lusical - Companhia Lusitana de Cal S.A, Indústria Mineral – Produção de Cales não-Hidráulicas, (E#07)) in the region install CO_2 capture technologies, capturing 85% of its emissions at the time. Simultaneously, the BA Glass, S.A. Fábrica da Marinha Grande (E#05) replaces its pilot by a large-scale capturing unit, being followed by former Santos Barosa - Vidros, S.A. (E#06), one of the biggest glass facilities in the region.

In 2040 CO_2 capture is deployed in the cement unit CIMPOR – Indústria de Cimentos, S.A., Centro de Produção de Souselas (E#08), and in two glass industries (E#10 and E#09).

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In 2045, the remaining cement industries in the region (Maceira E#11 and Pataias E#12) install capture technologies, enabling capture 85% of this sector's emissions. Due to the rising demand of biological CO_2, paper and pulp industries in the Lusitanian Basin region start capturing CO_2, namely About The Future-Empresa Produtora de Papel S.A. (E#13); Celbi (E#14) and Soporcel - Navigator Paper Figueira (E#15), thus creating a cluster in Figueira da Foz.

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Table 6: Identification of CO_2 emitter facilities of the Lusitanian Basin region

Scenario unit ID	Emitter ID	Facility name	Industry sector	CO2 emissions in 2018 (Mt/y)	Start Year	End Year	Capture rate
E#01	PT.ES.003	Centro de Produção de Souselas	Cement	0.89	2028	2039	0.06
E#02	PT.ES.016	Fábrica da Marinha Grande	Glass	0.09	2028	2034	0.10
E#03	PT.ES.005	Fábrica SECIL - Outão	Cement	0.84	2035	2050	0.85
E#04	PT.ES.002	Centro de Produção de Alhandra	Cement	0.94	2035	2050	0.85
E#05	PT.ES.016	Fábrica da Marinha Grande	Glass	0.09	2035	2050	0.85
E#06	PT.ES.014	Santos Barosa - Vidros, S.A	Glass	0.14	2035	2050	0.85
E#07	PT.ES.008	Indústria Mineral - Prod Cales não Hidráulicas	Cement	0.38	2035	2050	0.85
E#08	PT.ES.003	Centro de Produção de Souselas	Cement	0.89	2040	2050	0.85
E#09	PT.ES.018	GALLOVIDRO, S.A.	Glass	0.08	2040	2050	0.85
E#10	PT.ES.017	Verallia Portugal, S.A.	Glass	0.09	2040	2050	0.85
E#11	PT.ES.009	Fábrica Maceira-Liz	Cement	0.35	2045	2050	0.85
E#12	PT.ES.011	Fábrica Cibra-Pataias	Cement	0.27	2045	2050	0.85
E#13	PT.ES.010	About The Future-Empresa Produtora de Papel S.A.	Paper and pulp	1.31	2045	2050	0.90
E#14	PT.ES.019	Celbi	Paper and pulp	1.04	2045	2050	0.90
E#15	PT.ES.012	Soporcel (Navigator Paper Figueira)	Paper and pulp	0.44	2045	2050	0.90

In the long term, a dedicated CO_2 pipelines network is the only valid option for CO_2 onshore transport. A central pipeline with smaller branches connects the northern, central, and southern clusters to the storage site in S. Mamede (SU#01) and the intermediate storage facilities in Carriço (U#01), where CO_2 is to be stored in salt cavities prior to being utilised for synthetic fuels production.

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Some hubs are also created to optimise transportation. A total length of 310 km of CO_2 pipeline network is constructed by 2045, transporting an amount of CO_2 that ranges between 7.8 to 11.8 Mt CO_2/year.

In the long term, large amounts of CO_2 are needed to produce synthetic fuels, mainly methane, making this the largest destination for CO_2 in the Lusitanian Basin. Considering the carbon neutrality targets and the GWP accounting methodologies, only the CO_2 from bioenergy would be directed for such purposes, made possible by the fact that biomass would be a substantial part of the energy mix at the cement and paper and pulp industries.

Data presented in Table 7 summarizes all amounts of fossil and biogenic CO_2 emissions, from potential total emissions to captured emissions, final (net) emissions and CO_2 used in the production of synthetic fuels, namely methane, considering the information taken from Scenario ON_BEST for the Lusitanian Basin Region.

Table 7 - Fossil and biogenic CO_2 emissions from Scenario ON_BEST for the Lusitanian Basin Region

Mt/year	2018	2030	2035	2040	2045	2050
Factory + capture CO_2 emissions	6.860	7.272	8.530	8.462	10.433	10.433
fossil emissions	3.700	4.061	5.132	5.032	5.521	5.521
bio emissions	3.160	3.211	3.398	3.429	4.911	4.911
Non-captured CO_2 emissions	6.860	7.180	5.248	4.168	1.346	1.346
fossil non-captured	3.700	3.982	2.364	1.445	0.796	0.796
bio non-captured	3.160	3.198	2.884	2.722	0.549	0.549
Captured CO_2 emissions		0.092	3.282	4.294	9.087	9.087
fossil captured		0.079	2.768	3.587	4.725	4.725
bio captured		0.013	0.514	0.707	4.362	4.362
Bio CO_2 to methanation			0.513	0.706	4.361	4.361
Methane production			0.178	0.245	1.515	1.515

2.3.3 Rhône Valley (France)

Two scenarios were developed for the Rhône Valley, focusing on the Marseille cluster which gathers the biggest emitters of the Rhône Valley - ArcelorMittal's steel plant in Fos-sur-Mer featuring the most significant yearly CO_2 emissions. Furthermore, these emitters are quite close to each other, which would facilitate conditioning and transport logistics. Thereby, six plants were selected:

- ArcelorMittal (**steel plant**) in Fos-sur-mer, with reported 7.5 Mt CO_2/y and a targeted **capture rate of 10%**
- EVERE (**waste-to-energy plant**) in Fos-sur-Mer, with reported 0.40 Mt CO_2/y of which 56% biogenic CO_2, and a targeted **capture rate of 11%**

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- Petroineos Manufacturing France SAS (**refinery**) in Martigues, with reported 1.2 Mt CO_2/y and a targeted **capture rate of 48%**
- Air Liquide Hydrogène SMR Lavera (**H_2 plant**) in Martigues, with reported 0.18 Mt CO_2/y and a targeted **capture rate of 80%**
- Kem One Lavera (**chlorochemicals plant**) in Martigues, with reported 0.07 Mt CO_2/y and a targeted **capture rate of 20%**
- Lafarge Holcim (**cement plant**) in Septèmes-les-Vallons, with reported 0.43 Mt CO_2/y and a targeted **capture rate of 38%**

In the main scenario, CO_2 is firstly stored near Marseille in Camargue (natural park) until the site is saturated in 2039. Then, from 2040 to 2050, CO_2 is sent to another storage site in the Paris basin using existing oil & gas pipes. In the alternative scenario, the site in Camargue is not used and CO_2 is directly sent to the Paris basin from 2030. Figure 4 shows the general timeline of the CCUS scenarios and Table 8 details the transport modes and distances considered in both the main and the alternative scenario.

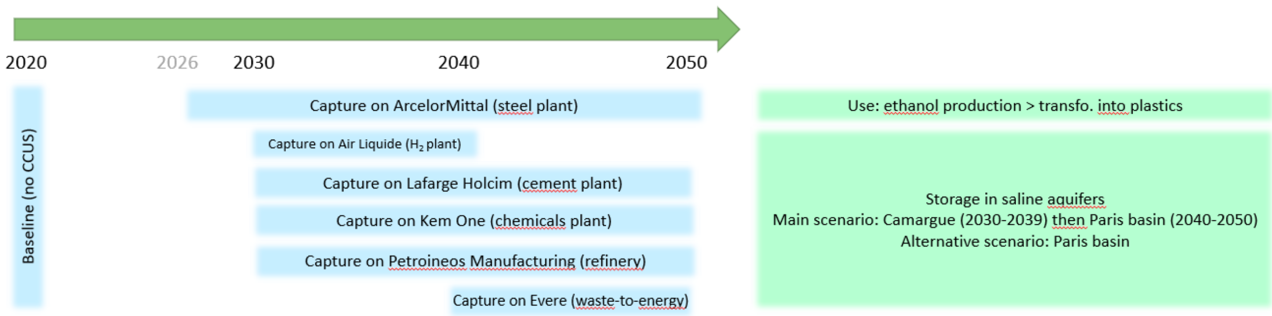

Figure 4: Timeline of the CCUS scenarios for the Rhône Valley (Marseille Cluster).

Table 8: Details on transport modes and distances in both CCUS scenarios for the Rhône Valley.

Scenario 1 (main case): 4 main emitters + 2 others, storage in Camargue until 2039 then in Paris basin						
Capture on	From	To	Transport	Transport details	Storage	Utilization
E#01 : steel plant	2026	2050	none		none	100% ethanol
E#02 : refinery	2030	2050	2030-2039 : Ship 2040-2050 : existing Oil (P#05) & Gas (P#06) pipes	2030-2039: 13,4 km pipe (P#01) + 52,4 km ship (S#01) 2040-2050: 13,4 km pipe (P#01) + 336,7 km pipe (P#05) + 292 km pipe (P#06) + 7 km pipe (P#07)	2030-2039 : Saintes-Maries-de-la-Mer 2040-2050 : Donnemarie-Trias (Paris basin)	none
E#03 : hydrogen	2030	2040	Ship	13,7 km pipe (P#02) + 52,4 km ship (S#01)	Saintes-Maries-de-la-Mer	none

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E#04 : waste-to-energy	2040	2050	Existing Oil (P#05) & Gas (P#06) pipes	5,2 km pipe (P#03) + 336,7 km pipe (P#05) + 292 km pipe (P#06)+ 7 km pipe (P#07)	Donnemarie-Trias (Paris basin)	none
E#05 : chemicals (chloro-chemistry)	2030	2050	2030-2039 : Ship 2040-2050 : existing Oil (P#05) & Gas (P#06) pipes	2030-2039: 14,4 km pipe (P#04) + 52,4 km ship (S#01) 2040-2050: 14,4 km pipe (P#04) + 336,7 km pipe (P#05) + 292 km pipe (P#06)+ 7 km pipe (P#07)	2030-2039 : Saintes-Maries-de-la-Mer 2040-2050 : Donnemarie-Trias (Paris basin)	none
E#06 : cement	2030	2050	2030-2039 : Ship 2040-2050 : existing Oil (P#05) & Gas (P#06) pipes	2030-2039: 54 km train (T#01) + 52,4 km ship (S#01) 2040-2050: 54 km train (T#01) + 336,7 km pipe (P#05) + 292 km pipe (P#06)+ 7 km pipe (P#07)	2030-2039 : Saintes-Maries-de-la-Mer 2040-2050 : Donnemarie-Trias (Paris basin)	none

Scenario 2 (alternative case) : 4 main emitters + 2 others, storage directly in Paris basin						
Capture on	From	To	Transport		Storage	Utilization
E#01 : steel plant	2026	2050	none		none	100% ethanol
E#02 : refinery	2030	2050	Existing Oil (P#05) pipe + Train	13,4 km pipe (P#01) + 336,7 km pipe (P#05) + 383 km train (T#02) + 13 km pipe (P#06)	Donnemarie-Trias (Paris basin)	none
E#03 : hydrogen	2030	2040	Existing Oil (P#05) pipe + Train	13,7 km pipe (P#02) + 336,7 km pipe (P#05) + 383 km train (T#02) + 13 km pipe (P#06)	Donnemarie-Trias (Paris basin)	none
E#04 : waste-to-energy	2040	2050	Existing Oil (P#05) pipe + Train	5,2 km pipe (P#03) + 336,7 km pipe (P#05) + 383 km train (T#02) + 13 km pipe (P#06)	Donnemarie-Trias (Paris basin)	none
E#05 : chemicals	2030	2050	Existing Oil (P#05) pipe + Train	14,4 km pipe (P#04) + 336,7 km pipe (P#05) + 383 km train (T#02) + 13 km pipe (P#06)	Donnemarie-Trias (Paris basin)	none
E#06 : cement	2030	2050	Existing Oil (P#05) pipe + Train	54 km train (T#01) + 336,7 km pipe (P#05) + 383 km train (T#02) + 13 km pipe (P#06)	Donnemarie-Trias (Paris basin)	none

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2.4 Functional unit

The functional unit is a comprehensive formulation of a system's function (i.e. action + performance + duration) for conducting an LCA. Indeed, it enables both to express the impact assessment results relatively to the given function, and to compare two systems with a similar function.

In the present case of regional CCUS scenarios assessment, two relevant functional units are selected in order to provide a useful picture of the net impacts of CCUS scenarios compared to the baseline situations:

- For the **first assessment level** focusing on intermediate years (2030, 2040 and 2050), the function of the **CCUS systems** is to "capture, transport, use and/or store a given amount of CO_2 from the selected set of emitters running their respective activities during the considered year"
  - the function of the **baseline system** can thus be express as follows: "selected emitters running their respective activities during the considered year, without carbon capture, and CCU-derived equivalent products being supplied through conventional pathways".
- For the **second assessment level** focusing on cumulative effects from 2020 to 2050, the function of the CCUS systems is to "capture, transport, use and/or store a given amount of CO_2 from a given set of emitters from 2020 to 2050".
  - the function of the **baseline system** can thus be express as follows: "selected emitters running their respective activities from 2020 to 2050, without carbon capture, and CCU-derived equivalent products being supplied through conventional pathways".

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3 Life cycle inventory

The life cycle inventory consists in listing all elementary material and energy input and output flows entering or exiting the considered system. Elementary flows are further combined and characterized to yield the environmental indicators to assess. Thereby, the LCA accounts for both direct and indirect consumptions and emissions all along the CCUS chains, which requires additional data compared to the TEA.

The modelling was implemented in the Simapro software using the **Ecoinvent LCA database to inform the impacts of background activities** (products and energy supply mixes etc.). However, it should be noted that the LCA has been performed by different organizations related to the regions - namely CIEMAT for the Ebro basin (Ecoinvent v3.7.1), Portuguese DGEG for the Lusitanian basin (Ecoinvent v3.4) and IFPEN for the Rhône Valley (Ecoinvent v 3.7.1). Consequently, both versions of the software and the database slightly differ according to the current update status in each organization. Nonetheless, we reviewed the potential background activities (e.g. MEA supply, NG supply...) and characterization factors (for impact assessment) that could be affected, and estimated that there should be no significant differences or bias resulting from the use of different but close versions of Ecoinvent. In particular, yearly Ecoinvent updates systematically include an update of regional electricity mixes (regarding the share in each energy source entering the mix; background data on energy supply per source remains stable), but as those are specifically modelled with prospective assumptions in this work, this is not a blocking point.

Data, parameters and assumptions set for the TEA in WP5 and also required for the LCA (see Table 9) were directly taken in order to align both assessments as much as possible.

Finally, **other foreground data** - i.e. input amounts of materials and energy, and output substances released to the environment (air, water, soil) - that is not reported in the Tool (useless for the TEA) was selected from a preliminary literature review of publications on CCU/CCS LCA. We followed a modular approach by separately reporting useful data and parameters that were considered in the selected publication on each main block of the CCUS chains: capture, conditioning, transport, use and storage. Then, for each block a publication was selected as a reference to feed the Simapro modelling, according to its relevance based on combined temporal (recent publication), comprehensiveness (complete inventory data) and representativeness (global setting compliance with the actual emitters or use cases of the regional scenarios regarding e.g. the scaling of the plant, the conditioning pressure or temperature etc.) considerations.

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Table 9: key parameters common to the TEA and LCA.

Capture rate	**Identical to TEA assumptions per emitter (from Capture Module)**
Capture efficiency	Identical to TEA assumption for the Ebro and Lusitanian basins, 90% for the Rhône Valley (instead of 80% for the TEA) = already achievable efficiency acc. to literature and industrials
Baseline CO_2 emissions (without capture)	Identical to TEA assumptions per emitter (WP2 DB)
Additional CO_2 emissions with capture (due to internal energy provision)	Identical to TEA assumptions per emitter (from Capture Module)
Fuel mix for capture-related energy provision	Identical to TEA assumptions per emitter (from Capture Module)

3.1 Capture processes

Table 10 summarizes the emitters that are included in the perimeter of each regional CCUS system. In the following subsections, information on life cycle inventory data used and adapted is provided, as well as any modelling difference for a same emitter type in different regions.

In France and Portugal, the capture infrastructure for each emitter is modelled with data taken from (van der Giesen, et al., 2017) regarding the required low-alloyed steel and stainless steel and considering a 30 years lifetime. Moreover, emissions of other compounds that may be released to the atmosphere through the capture process (mostly resulting from MEA degradation) - namely acetaldehyde, formaldehyde, ammonia and MEA – are informed using data from (Singh, et al., 2011) (dealing with capture on a natural gas combined cycle power plant) as this publication was part of the only ones providing it. The reported figures were actually further used by a couple of other authors (Fadeyi, et al., 2013) (van der Giesen, et al., 2017) (Giordano, et al., 2018). Finally, NOx and SOx emissions from the plants could not be informed (no data found).

Capture processes **in the Spanish case** have been modelled following suggestions and foreground data from the French case and adapting background data to the Spanish context, i.e. materials consumption, distances, and energy mixes. As the CO_2 capture technologies require significant amounts of energy, special focus was paid to this aspect. Additionally, data regarding emissions and life-time was taken from (Garcia-Herrero *et al.*, 2016) (D. García-Gusano *et al.*, 2015) (Diego García-Gusano *et al.*, 2015).

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Table 10: Summary of the emitters included in the perimeter of each regional CCUS system.

	Ebro Basin (ES)	Lusitanian Basin (PT)	Rhone Valley (FR)
Natural gas power plant	1		
Biomass power plant	1		
Waste-to energy-plant			1
Steel plant			1
Cement plant	1	1	1
Refinery			1
Chemicals plant	1		1
Hydrogen plant			1
Glass plant		1	
Paper and pulp plant		1	

3.1.1 Natural gas power plant

The first-generation capture technologies have proven that carbon capture applied to natural gas power plants is an available technology and can be scaled for commercial application. No comprehensive inventory was found to specifically model capture on Natural gas Power plants. Information from (Markewitz *et al.*, 2019) dealing with a natural gas combined cycle power plant was used to approximate capture on the Spanish Natural Gas power plant.

3.1.2 Biomass power plants

In Spain, the use of biomass power plant is low, despite the new plants. Until 2019, the installed capacity was 518 MW. The main use of this energy source in Spain is for thermal energy that is used for heating, production of sanitary hot water and as a contribution to certain industrial processes. However, it is clear the fundamental role of biomass in ensuring the management of the electrical system and being able to meet the renewable energy targets set for 2030.

3.1.3 Waste-to-energy plant

No comprehensive inventory was found to specifically model capture on waste-to-energy plants. Therefore, information from (Fadeyi, et al., 2013) dealing with a natural gas combined cycle power plant was used to approximate capture on the French waste-to-energy plant regarding the MEA make-up, water, activated carbon and sodium hydroxide consumptions.

Energy consumption for capture is internally provided as considered for the TEA: the corresponding supply of natural gas (50% of the required energy) is accounted for in the LCA model (upstream impacts according to the Ecoinvent process "Heat, district or industrial, natural gas, industrial furnace >100kW"), while the combustion-related CO_2 emissions are those indicated in the Tool. The

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remaining 50% required energy is generated with refused derived fuel (RDF) which is considered as waste and thus bears no upstream impacts. The global share of biogenic CO_2 emitted both through the plant and capture operations is proportionally accounted for in the non-captured emissions (biogenic CO_2 emitted being climate neutral) and final storage (storage of biogenic CO_2 resulting in negative emissions).

3.1.4 Steel plant

In the Rhône Valley, capture on the steel plant is modelled according to the inventory data from (Chisalita, et al., 2018) in which the studied case consists of a steel plant producing 4 Mt steel/y (identical to the reference plant in the Tool) and emitting 10.4 Mt CO_2/y (in line with the reference plant in the Tool emitting 8.4 Mt CO_2/y). Data include MEA and water consumptions, and a CO_2 leak of 0.05% CO_2 captured is indicated in the publication. Upstream impacts of natural gas supply for capture energy consumption (4.88 MJ/kg CO_2 captured) are accounted for.

3.1.5 Cement plants

Data on capture applied to the French and Portuguese cement plants is comprised of a MEA make-up of 2.099 kg/t CO_2 captured, as indicated in (An, et al., 2019) who assessed the environmental impacts of capture on a cement plant (yielding 1 Mt cement/y as the reference plant in the Tool); the infrastructure (as previously described); and the upstream impacts of natural gas and other fuels supplying capture energy needs. In France, energy is generated with 63% natural gas and 37% refused derived fuel (RDF) which is considered as waste and thus bears no upstream impacts. In Portugal, the energy mix evolves as detailed in WP5 work. The sector has adopted its own neutrality goal up to 2050, resulting in a gradual replacement of petcoke with alternative waste streams, biomass and blending of natural gas and hydrogen. In 2030, about 60% of the fuel is of biogenic origin, evolving to a mix of fuels in the interval of 80 to 90% of biogenic origin, among the group of emitters.

3.1.6 Refinery

No comprehensive inventory was found to specifically model capture on refineries. The publication from (Young, et al., 2019) deals with it but does not provide useful information for the modelling. Thereby, the MEA make-up was approximatively set to 1.5 kg/t CO_2 captured, which is the mean value found in the investigated literature for capture on other emitters (i.e. values range from 1 to 2 kg MEA make-up/t CO_2 captured). Natural gas is again used for capture energy provision (5.52 MJ/kg CO_2 captured) so its supply impacts are accounted for.

3.1.7 Chemicals plants

Capture on the French chlorochemicals plant was considered to require the same inputs and yield the same outputs as capture on the refinery, due to a lack of data and considering the main inputs (MEA make-up etc.) are prone to be very similar no matter the emitter type.

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3.1.8 Hydrogen plant

Specific inventory data regarding capture on a hydrogen plant was not found. Therefore, as was done for the refinery the MEA make-up for capture on was approximatively set to a mean value of 1.5 kg/t CO_2 captured. Upstream impacts of natural gas supply for internal energy provision (0.75 MJ/ kg CO_2 captured) are accounted for.

3.1.9 Glass plant

At the glass sector, an increase of glass packing demand is expected. However, such glass production growth is not reflected in an increase in energy use and CO_2 emissions, due to the adoption of more efficient furnaces and expansion of glass cullet incorporation in the production process. Exhaust emissions from the furnaces are considered similar enough to the cement exhaust gases, so the same specific inventory regarding capture can be used. Thus, the values and references presented in section 3.1.5 are also valid for the glass emitter facilities.

3.1.10 Paper & pulp plant

Concerning the paper and pulp sector, a rise in paper and pulp production is expected. However, this does not mean that this increase is directly translated into higher CO_2 emissions, as the sector has been implementing mitigation measures, including energy efficiency and fuel substitution. Moreover, several paper and pulp units are using co-generation of heat produced together with black liquors – a waste product from its own pulp production process. Additional measures such as the conversion of fuel oil boilers to natural gas are also planned. The specific inventory regarding capture in the paper and pulp sector is considered to be the same as the above described, for the cement and glass sectors.

3.2 Conditioning and transport processes

3.2.1 Compression (for pipeline transport, gaseous state)

Compression is modelled with the required electricity input taken as **87.7 kWh/t CO_2** corresponding to the mean value between those indicated in (Koornneef, et al., 2008) (111 kWh/t CO_2) and in (Giordano, et al., 2018) (64.5 kWh/t CO_2), both for a compression to 110 bar.

3.2.2 Liquefaction (for train & ship transport)

An amount of **206 kWh/t CO_2** electrical consumption for liquefaction is considered as in JRC's 2020 WTW studies regarding the liquefaction of CO_2 for e-fuels production (JRC, 2020).

3.2.3 Pipeline transport

The Ecoinvent dataset "Transport, pipeline, long distance, natural gas" (expressed per tkm) was copied and adapted to model the transport of CO_2 in the considered regions during a given year: the electricity source (for re-compressions) was set to the national grid mix; all natural gas-related

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fugitive emissions during transport were removed and only a CO_2 leakage rate per tkm is left, considering a **0.00026% mass rate per km travelled** based on (Antonini, et al., 2020).

3.2.4 Ship transport

In the main scenario for the Rhône Valley, the Ecoinvent dataset "Transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas {GLO}" (expressed per tkm) was directly used. It contains the inventory for ship infrastructure as well as operating and maintenance, amortized per tkm.

3.2.5 Train transport

Train transport (occurring in both scenarios for the Rhône Valley) was also modelled with an available Ecoinvent dataset of perimeter similar to the ship transport dataset (i.e. inventory for infrastructure, operating and maintenance amortized per tkm), "Transport, freight train" located in the studied region.

3.3 Storage

Only the required electricity for injection into the storage sites is modelled due to both a lack of data on e.g. monitoring-related inputs, and the expected negligible contribution of such inputs to the global environmental impacts off CCS value chains. A consumption of **7 kWh/t CO_2** injected was considered according to (Chisalita, et al., 2018).

3.4 Utilization pathways

3.4.1 Ethanol production

ArcelorMittal's steel plant is the only emitter of the Rhône Valley on which capture is intended for CO_2 utilization. ArcelorMittal aims to use a share of the captured CO_2 to produce ethanol on-site, which would be further processed into plastics[2]. Therefore, only the upstream ethanol production differs between the baseline and the CCUS scenarios, while the upgrading into plastics and final use would yield identical impacts. The perimeter for this assessment thus stops at the ethanol production unit gate both for CO_2-derived ethanol and conventional ethanol (baseline).

Inventory data on **ethanol production from CO_2 in CCUS scenarios** is derived from (Thonemann & Pizzol, 2019). The modelled pathway is an electro-reduction process via syngas according to the following synthesis equation:

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[2] https://www.fo-arcelormittal-fos.fr/blog/c/0/i/51149720/fos-sur-mer-arcelormittal-mediterranee-se-lance-dans-l-acier-vert

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$$2\ CO_2 + 3\ H_2O \rightarrow C_2H_5OH + 3\ H_2 + 3\ O_2$$

The process consumes electricity which is assumed to be 100% renewable, namely generated from a wind farm ("Electricity, high voltage {FR}| electricity production, wind, 1-3MW turbine, onshore"), to comply with expected market incentives on the use of renewable power. The required heat from steam is produced according to the Ecoinvent European technology mix "market for heat, from steam, in chemical industry". Finally, ultrapure process water is also required. In the end, a small amount of CO_2 remains as a co-product of ethanol, i.e. 0.05 t/t CO_2 processed, which is assumed to be vented to the atmosphere.

Conventional ethanol in the baseline scenario is considered to be supplied via catalytic hydration of ethylene:

$$C_2H_4 + H_2O \rightarrow C_2H_5OH$$

Indeed, the fermentation pathway is the second widely used option, but ethanol for industrial purposes as in the present case (plastic production) is rather produced from ethylene. The Ecoinvent dataset "market for ethanol, without water, in 99.7% solution state, from ethylene {RER}" is directly used as such to model this conventional pathway. Along with heat (from natural gas) and electricity (average European grid mix), the process consumes deionised water, various chemicals (acids and NaOH) and benzene while it yields diethyl ether as a co-product of ethanol, along with direct emissions to air (including CO_2) and water, and wastewater.

3.4.2 Methanol production

Recent studies demonstrate an interest in the use of alcohols, such as methanol (MeOH), as fuel in sectors that are difficult to decarbonize, like maritime and aviation (Garcia-Garcia *et al.*, 2021).The production of methanol from direct CO_2 hydrogenation is of interest, due to its potential to mitigate fuel combustion-related CO_2 emissions. The methanol production from direct CO_2 (using pure sources of CO_2 and green H_2) has several advantages over the conventional process—it results in significantly fewer by-products and requires less energy for product purification (Borisut P and Nuchitprasittichai A (2019)). The methanol production and use have been considered in this scenario given the current national strategy for moving out of the traditional fossil fuels and the strong methanol demand from the chemical industry. Inventory data on methanol production through CO_2 hydrogenation in the CCUS Spanish scenario is derived from (Wang *et al.*, 2020) and (Mccord and Stokes, no date).

The modelled pathway follows the synthesis reactions of MeOH production:

$$CO2 + 3H2 \rightarrow \mathrm{CH3Oh} + H2O$$

$$CO2 + H2 \rightarrow CO + H2O$$

Methanol can be transformed into ethene, propene, formaldehyde, acetic acid and other products usually derived from petrochemicals, which is out of scope here.

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3.4.3 Methanation

Carbon dioxide captured from flue gases or raw biogas can be combined with renewable hydrogen (H_2) from water electrolysis to produce basic chemicals, such as methane or methanol, which may then be used to produce polymers and other chemicals.

H_2 is produced by electrolysis, using renewable energies, thereby minimizing GHG emissions along the value chain. In this study we assume the supply of wind energy for electrolysis and the Portuguese electricity mix for all other processes.

The chemical reaction occurring for methane production from CO_2 and H_2, also called CO_2 methanation, is described by Sabatier's reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \ (\Delta H_R{}^0 = -253.2 \text{ kJ/mol})$$

Sabatier's reaction is highly exothermal and, thus, it produces not only the methane, but also a considerable amount of heat. This is an opportunity to explore process integration possibilities resulting in important energy efficiency improvements and GHG reductions. The values used and respective Ecoinvent datasets are presented in Table 11.

Table 11: Inputs and outputs of methanation reaction (adapted from Collet et all 2017).

Inputs		
CO_2	1	ton
Electricity, high voltage {PT}| production mix (relevant year)	50,5	kWh
Hydrogen from wind energy	6212,8	kWh
Outputs		
Natural gas, high pressure {Europe without Switzerland}	534,8	m3
Heat, central or small-scale, natural gas {Europe without Switzerland}	4117	MJ

3.5 Electricity production/consumption mix over time

3.5.1 Prospective mix in Spain

Spain's Integrated National Energy and Climate Plan INECP 2021-2030 (MITECO, 2019) is aimed at making progress with decarbonisation, laying down a firm foundation for consolidating a climate-neutral path for the economy and society by 2050. In this regard, it should be noted that in Spain, around three of every four tonnes of greenhouse gases originate in the energy system; therefore, decarbonisation of this system is the essential element on which the energy transition will be based. However, among the challenges and opportunities associated with this Programme is that to impacting on strategies and policies in different sectors, therefore inter-sectoral coordination will be necessary to make the various policies compatible. According to the INECP, renewable electricity generation in 2030 will represent 75% of the total, consistent with a path towards a 100% renewable electricity sector in 2050. It should be noted that there will be an additional 6 GW of storage,

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providing greater capacity for managing generation. In this sense, the Programme foresees that by 2030 there will be an additional capacity of 6 GW of pumps and batteries (Large-scale (GW) in terms of reversible hydroelectric and Storage in networks (MW) in terms of cells and batteries). Table 12 shows the composition of the Spanish electricity grid mix assumed in the context 2021 – 2030.

Table 12: composition of the Spanish electricity grid mix assumed in the context 2021 - 2030

Power source	Technology sharing Spanish context 2018[2]	Technology sharing in Spanish context 2021-2025 (%)	Technology sharing in Spanish context 2030[1] (%)
Hard coal	(%)	23.6	
Lignite	16.0	3.6	
Oil	1.0	8.2	0.3
Natural gas	5.0	19.0	9.5
Industrial gas	9.0	0.4	4.1
Hydropower		11.3	8.2
Hydropower, at pumped storage	15.0	1.0	2.0
Nuclear	2.0	22.1	7.2
Production mix photovoltaic	22.0	0.0	20.4
Wind power plant		5.6	34.5
Cogeneration ORC 1400kWth, wood	21.0	1.5	2.4
CSP	1.0		6.7
Cogen with biogas engine	2.0	0.5	2.7
Storage in networks	0.2		2.0
Production mix FR		2.2	
Production mix PT	2.0	0.8	
Total – GHG intensity (g CO2eq./kWh)	3.0	519	150
Total - CED (MJeq/kWh)	332	10.48	7.24

[1] Use for alternative scenario (75% renewable)

[2] Ecoinvent Database

3.5.2 Prospective mix in Portugal

The energy mix used for Portugal is extracted from the most recent version of the national energy model used in the National Strategy for H_2, published in 2020. The reference year is 2018 and the model includes the prospective energy mix sources and the energy import/export balance until

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2050. The transmissions losses are assumed to be constant, around 4%, and are also included in the calculations. This energy mix life cycle carbon footprint is decreasing towards 2050, as it is envisioned in the 2050 Carbon Neutrality Roadmap of Portugal. The values used and respective ecoinvent datasets are presented in Table 13.

Table 13: EN-H2 prospective energy mix up to 2050.

Power source	% in 2018	% in 2030	% in 2035	% in 2040	% in 2045	% in 2050	Supply activities
Coal	2.0	0.0	0.0	0.0	0.0	0.0	Electricity, high voltage {PT}| electricity production, hard coal
Waste	1.0	0.8	0.7	0.6	0.6	0.6	Electricity, medium voltage {PT}| electricity, from municipal waste incineration to generic market for
Natural gas	20.9	11.5	9.1	6.1	3.0	0.0	Electricity, high voltage {PT}| electricity production, natural gas, combined cycle power plant
Hydrogen	0.0	0.0	0.0	0.6	1.9	1.6	Electricity, Fuel Cell with renewable hydrogen
Wind power	25.1	27.6	27.4	27.3	27.0	27.3	Electricity, high voltage {PT}| electricity production, wind, >3MW turbine, onshore
Offshore Wind power	0.0	1.0	2.9	4.9	6.9	8.1	Electricity, high voltage {PT}| electricity production, wind, 1-3MW turbine, offshore
Photovoltaic	4.0	18.6	21.9	25.0	27.1	29.6	Electricity, low voltage {PT}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
Decentralised Photovoltaic	0.0	1.6	2.3	2.9	2.8	2.8	Electricity, low voltage {PT}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted
Large Hydro power	28.2	27.1	24.9	21.5	20.4	19.0	Electricity, high voltage {PT}| electricity production, hydro, reservoir, non-alpine region
Small hydro	3.4	2.7	2.4	2.1	2.0	1.8	Electricity, high voltage {PT}| electricity production, hydro, run-of-river
Waves, tides, ocean energy	0.0	1.7	2.9	4.0	4.5	5.0	Electricity, high voltage {PT}| electricity production, hydro, run-of-river

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Biomass (woody)	2.6	2.5	2.4	2.3	2.2	2.3	Electricity, high voltage {PT}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
Biogas	0.6	0.1	0.1	0.1	0.1	0.1	Electricity, high voltage {PT}| heat and power co-generation, biogas, gas engine
Geothermal	0.0	0.0	0.2	0.5	1.3	2.0	Electricity, high voltage {PT}| electricity production, deep geothermal
Import ES	12.1	4.8	2.8	2.2	0.3	-0.2	Electricity, high voltage {PT}| import from ES
Transmission losses	4.0	4.0	4.0	4.0	4.0	4.0	Electricity, high voltage {PT}| production mix
Total – GHG intensity (g CO2eq./kWh)	192	115	94	80	63	49	DGEG EN-H2 scenarios

3.5.3 Prospective mix in France

In France, the national Electricity Transport Network (RTE) has built prospective scenarios regarding the electricity production mix within 2050 in order to derive the associated requirements to reach the carbon neutrality target in this sector[3]. A default "100% renewable" electricity mix in 2050 as described by RTE was taken in the CCUS scenarios for the Rhône Valley. Thereby, it is assumed that the mix composition and related environmental impacts would linearly evolve between 2020 and 2050. The 2020 *consumption* mix is modelled with available RTE consolidated data for the year 2019[4]. The 2050 mix is only a *production* mix, i.e. neither projections on import-export nor the related prospective mixes of the exchanging countries were comprehensively available to model the final consumption mix. However, a first analysis has shown little impact contribution of the various electricity consumption points of the Rhône Valley CCS chains (conditioning, transport and storage) in terms of GHG emissions, so switching from production to consumption mixes is not expected to have significant repercussions on both the absolute results and the observations made.

In addition, RTE prospective mix including 50% nuclear power in 2050 was also modelled to test the sensitivity of the results to the assumed 2050 mix (results only discussed in section 4.2.3).

Both the compositions of the mixes and the related background power production activities per source are indicated in Table 14. The sub-shares per technology (e.g. natural gas combined cycle, co-

[3] https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques

[4] https://www.rte-france.com/en/eco2mix/download-indicators

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generation etc.) are not indicated here for the sake of simplification but are integrated into the modelling.

Table 14: composition of the French electricity grid mixes assumed in 2020 and 2050.

Power source	% in 2020	% in 2050 – 100% renewable	% in 2050 – 50% nuclear	Supply activities
Hydro power	11.1%	9%	10.1%	Electricity, high voltage {FR}| electricity production, hydro, run-of-river Electricity, high voltage {FR}| electricity production, hydro, reservoir, alpine region Electricity, high voltage {FR}| electricity production, hydro, pumped storage
Wind power	6.30% onshore	21% onshore, 31% offshore	13.1% onshore, 12.1% offshore	Electricity, high voltage {FR}| electricity production, wind, 1-3MW turbine, onshore Electricity, high voltage {FR}| electricity production, wind, 1-3MW turbine, offshore
Photovoltaic	0%	36%	13%	Electricity, low voltage {FR}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
Biomass (waste, biogas, wood)	0.98%	2%	2%	Electricity, for reuse in municipal waste incineration only {FR}| treatment of municipal solid waste, incineration Electricity, high voltage {FR}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 Electricity, high voltage {FR}| heat and power co-

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				generation, biogas, gas engine
Nuclear	70.0%		50.3%	Electricity, high voltage {FR}| electricity production, nuclear, pressure water reactor
Oil & coal	0.99%			Electricity, high voltage {FR}| electricity production, hard coal Electricity, high voltage {FR}| heat and power co-generation, oil Electricity, high voltage {FR}| electricity production, oil
Natural gas	6.89%			Electricity, high voltage {FR}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical Electricity, high voltage {FR}| electricity production, natural gas, combined cycle power plant Electricity, high voltage {FR}| electricity production, natural gas, conventional power plant
Import GB	0.16%			Electricity, high voltage {FR}|Import from GB
Import ES	0.60%			Electricity, high voltage {FR}|Import from ES
Import IT	0.04%			Electricity, high voltage {FR}|Import from IT
Import CH	0.22%			Electricity, high voltage {FR}|Import from CH
Import DE + BE	2.26%			Electricity, high voltage {FR}|Import from DE Electricity, high voltage {FR}|Import from BE
Total – GHG intensity (g CO2eq./kWh)	73.6	39.2	20.3	

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4 Life cycle impact assessment (LCIA)

4.1 Characterization methods and selected indicators

Based on both the relevance of impact categories regarding the system studied and inventory data availability to enable characterization (e.g. if no information is available on water flows, water-related indicators such as the water scarcity footprint cannot be computed), the analysis was restricted to the following indicators: Climate change (IPCC, 2013) and Cumulative Energy Demand (CED) (Hischier, et al., 2010).

The impact on climate change is related to the radiative forcing over 100 years of all emitted greenhouse gases, expressed in kg CO_2 equivalent (eq.) (i.e. the radiative forcing of each GHG is normalized according to the one of CO_2). The cumulative energy demand represents the cumulated renewable and non-renewable energy demanded over the system's life cycle. It is expressed in MJ (HHV-based).

4.2 LCIA results

4.2.1 Ebro basin

4.2.1.1 Climate change

BSLT Scenario (main scenario)

The net impact on climate change of the main CCUS scenario from 2021 (corresponding to the baseline situation) to 2050 is shown in Figure 5 for intermediate years. The year 2027 is represented as it corresponds to the start of capture on the chemical industry.

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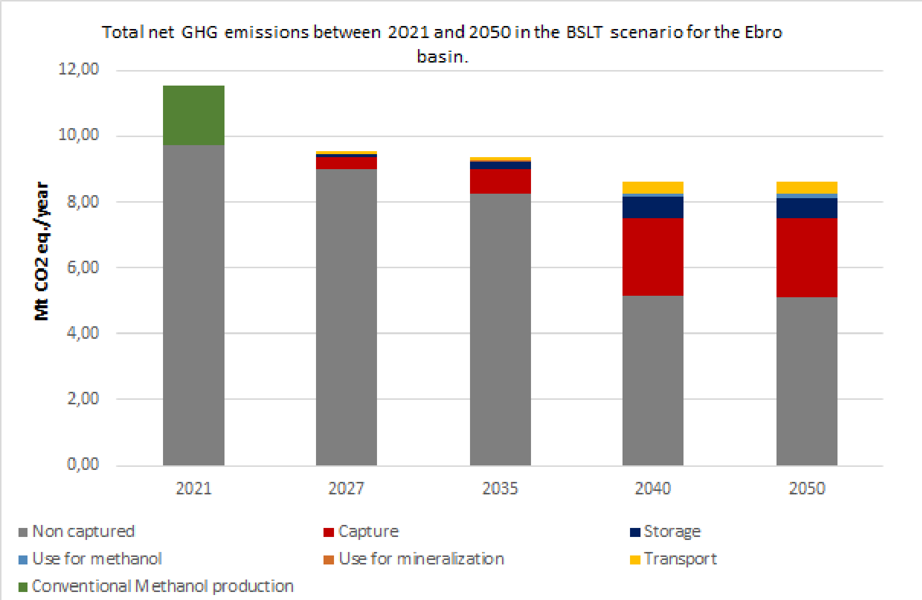

Figure 5: Total net GHG emissions between 2021 and 2050 (intermediate years) in BSLT scenario for Ebro basin

Impacts of conventional methanol production mainly come from natural gas (feedstock) and heat consumption from natural gas (Figure 5).

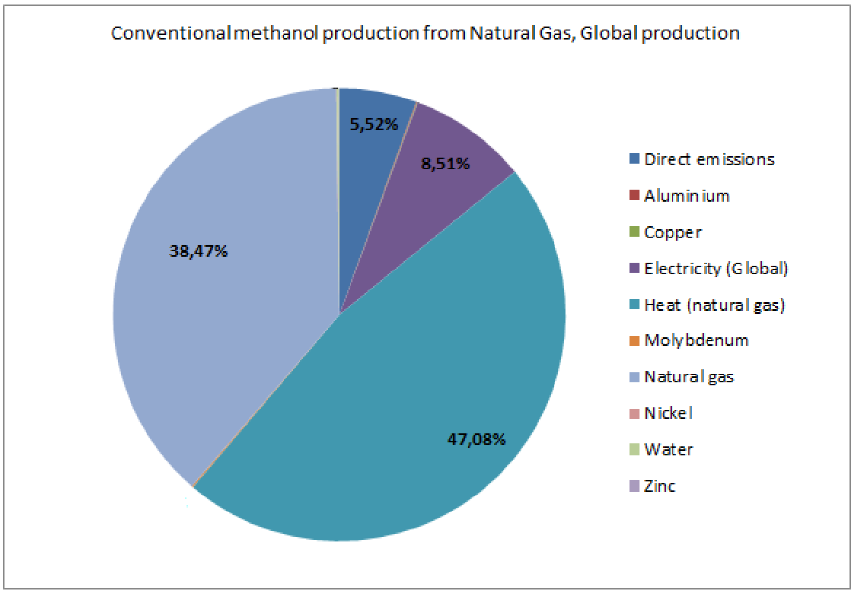

Figure 6: climate change impact contributions to conventional methanol production and CO2-derived methanol production.

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In terms of GHG emissions, the substitution of conventional methanol supply induces a net benefit because of CO_2 capture and also for the substitution of Natural Gas as fuel and feedstock (Figure 6).

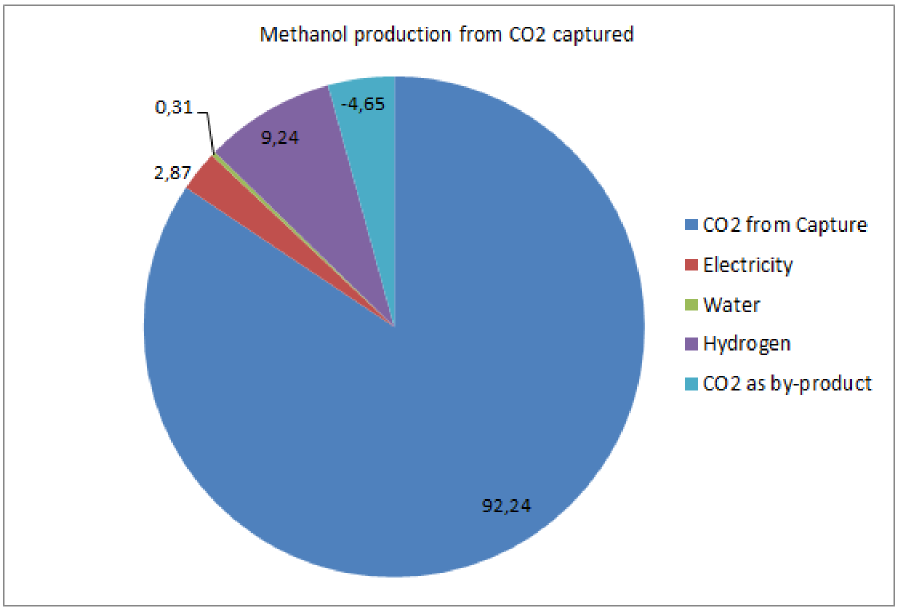

Figure 7: climate change impact contributions to methanol from CO2

For the BSLT scenario, the trend is a net decrease in GHG emissions associated with the selected emitters from 2027 to 2050, where a stabilized drop by 25% (approx. 3 Mt CO_2eq./y) can be expected compared to 2021 (baseline situation).

The total net GHG emissions related to the baseline situation amount to 11.56 Mt CO_2eq./y, of which 9.73 Mt CO_2eq./y correspond to the yearly CO2 emissions of the regarded emitters without capture. Of this total, 5.77 Mt CO_2eq./y are emitted by the Tarragona Cluster and 3.63 Mt CO_2eq./y by the Barcelona Cluster. The refinery and Cement industry are the major contributors.

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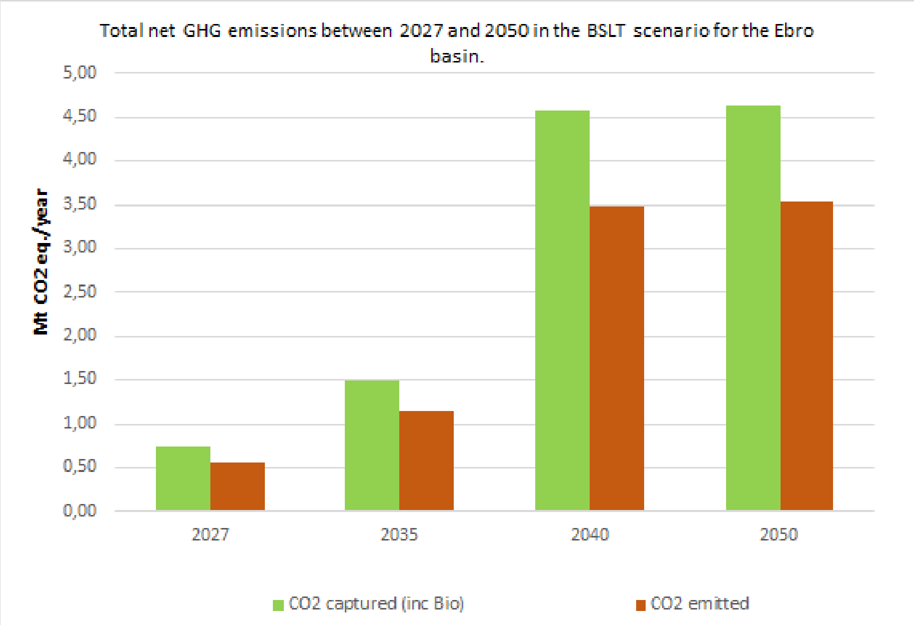

Figure 8: CO2 emissions captured versus CO2eq emissions induced by CCUS operation between 2027 and 2050

ISLT Scenario (Alternative scenario)

The net impact on climate change of the alternative CCUS scenario from 2021 (corresponding to the baseline situation) to 2050 and for intermediate years is shown in Figure 8. The year 2033 is represented as it corresponds to the start of implementing capture on the cement industry. In the alternative scenario, only the electricity mix is modified for 2030 onwards.

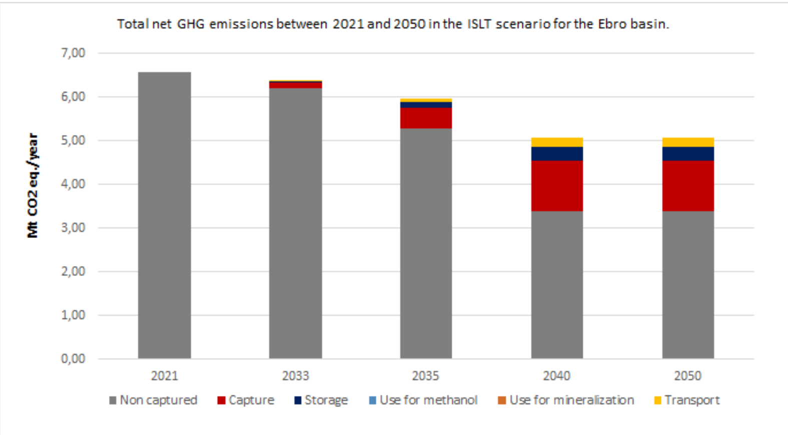

Figure 9: Total net GHG emissions between 2021 and 2050 (intermediate years) in ISLT scenario for Ebro basin

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In the same form as the BSLT scenario, in the ISLT scenario, the trend is a net decrease in GHG emissions associated with the selected emitters from 2033 to 2050, where a constant drop by 21% (1.34 Mt CO_2eq/y) can be expected compared to baseline situation for 2021. The total net GHG emissions related to the baseline situation amount to 6.58 Mt CO_2eq./y, of which 6.39 Mt CO2eq./y correspond to the yearly CO_2 emissions of the regarded emitters without capture and 0.21Mt CO_2eq. to process emissions (Figure 9).

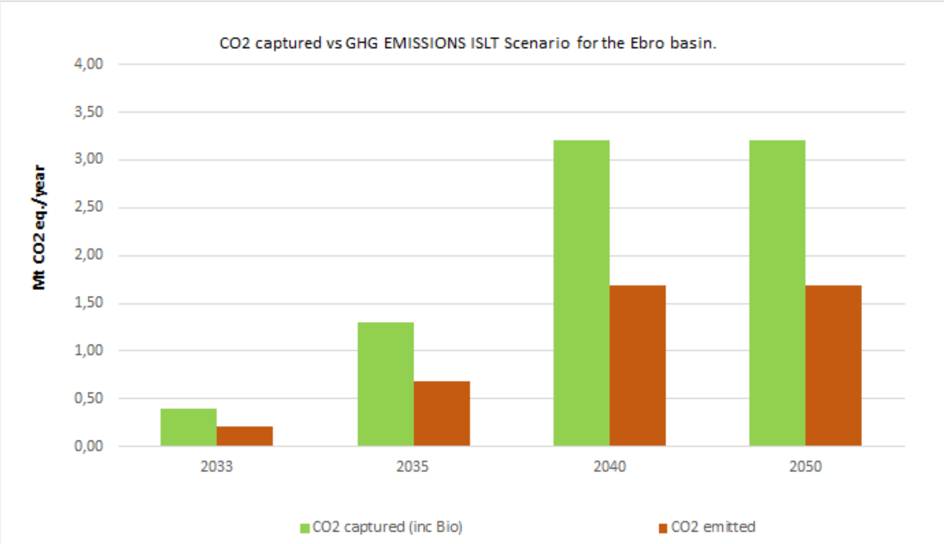

Figure 10: CO2 emissions captured versus CO2eq emissions induced by CCUS operation between 2033 and 2050

4.2.1.2 Cumulative Energy Demand

BSLT Scenario (main scenario)

The CED (renewable and non-renewable) of the BSLT scenario in intermediate years from 2027 to 2050 is shown in Figure 10. A comparison of CED in the baseline scenario corresponds to the conventional methanol production from 2021 to 2050 is also depicted in the same Figure.

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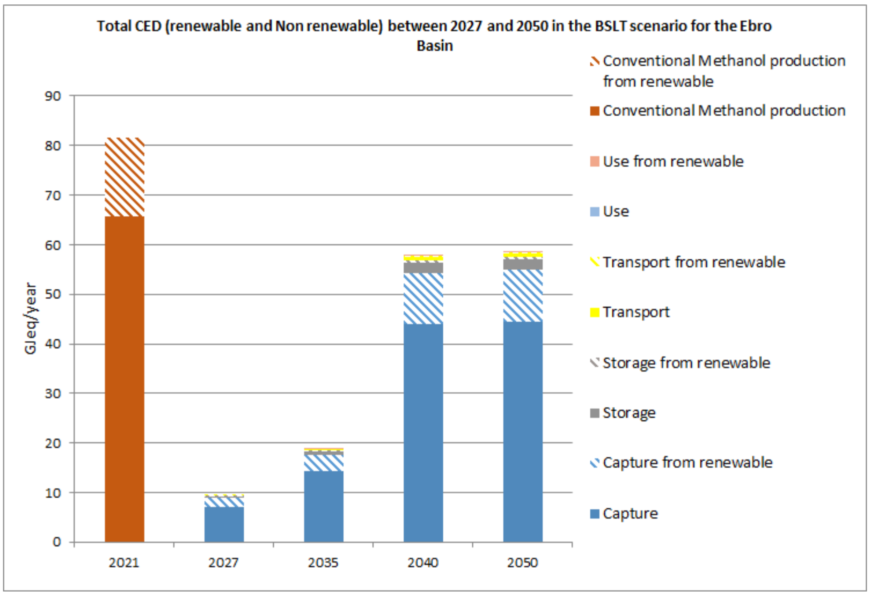

Figure 11: cumulative energy demand (CED) between 2020 and 2050 for intermediate years in the main scenario for BSTL Ebro Basin

ISLT Scenario (Alternative scenario)

The net impact on CED alternative CCUS scenario from 2033 (corresponding to the baseline situation) to 2050 and for intermediate years is shown in Figure 11. In the alternative scenario, only the electricity mix is modified for 2030 onwards.

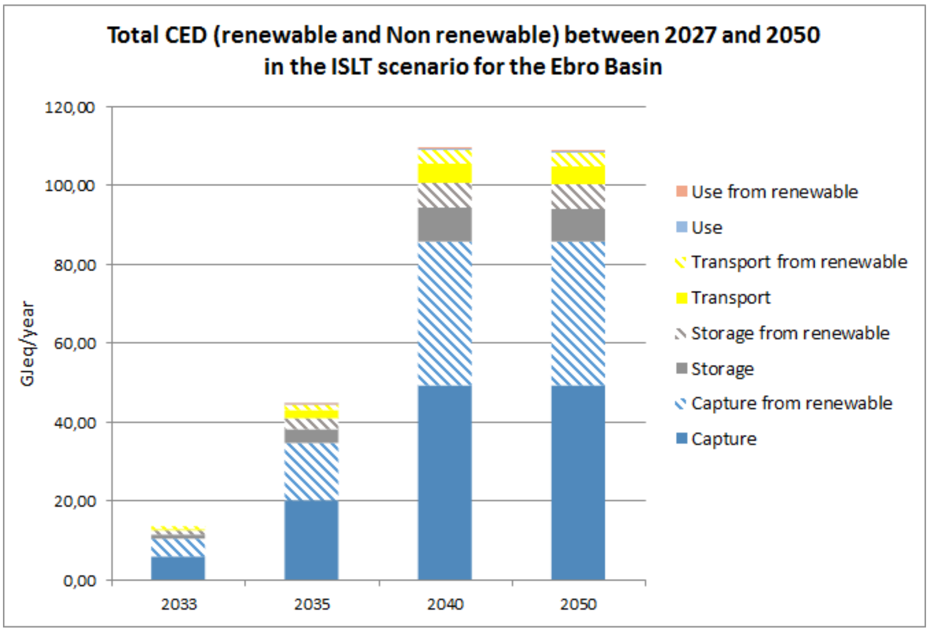

Figure 12: cumulative energy demand (CED) between 2033 and 2050 for intermediate years in the alternative scenario for Ebro Basin

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4.2.2 Lusitanian basin

4.2.2.1 Climate change

Using the information and data collected from WP5 (Strategic Plans), a life cycle model was developed according to the methods presented in section 2 and the inventory data in section 3. Table 15 presents the results of the life cycle impact assessment in terms of global warming potential, expressed in million tons of carbon dioxide equivalents (Mt CO_2eq). It should be highlighted that the results only include the fossil carbon GHG emissions, since it is considered that the biogenic carbon emissions have no global warming potential (or GWP = 0 kg CO_2eq).

Table 15: Life cycle PT Scenario ON_BEST emissions and capture data on GWP (Mt CO_2e)

GWP (Mt CO_2eq/year)	2018	2030	2035	2040	2045	2050
Factory + capture GHG emissions						
LC fossil emissions	3.700	4.064	5.220	5.236	5.888	5.835
Non-captured CO_2 emissions						
LC fossil non-captured	3.700	3.985	2.452	1.649	1.163	1.110
Captured CO_2 emissions		0.092	3.282	4.294	9.087	9.087
fossil captured		0.079	2.768	3.587	4.725	4.725
bio captured		0.013	0.514	0.707	4.362	4.362
Bio CO_2 to methanation						
Methane production			0.185	0.254	1.565	1.562
Methane &heat production credit			-0.264	-0.363	-2.241	-2.241
Life Cycle GWP (Mt CO_2eq/year)	3.700	3.985	2.373	1.540	0.487	0.431

The results for the LCIA of the main scenario (ON_BEST) for the Lusitanian basin region presented above include the biogenic emissions carbon capture and use (BECCU), through the methane production using renewable hydrogen and the captured biogenic CO_2. The outputs of this methanation process, as shown in Table 15, has a positive effect in the environment, here shown as a negative value on the impact category of climate change (GWP).

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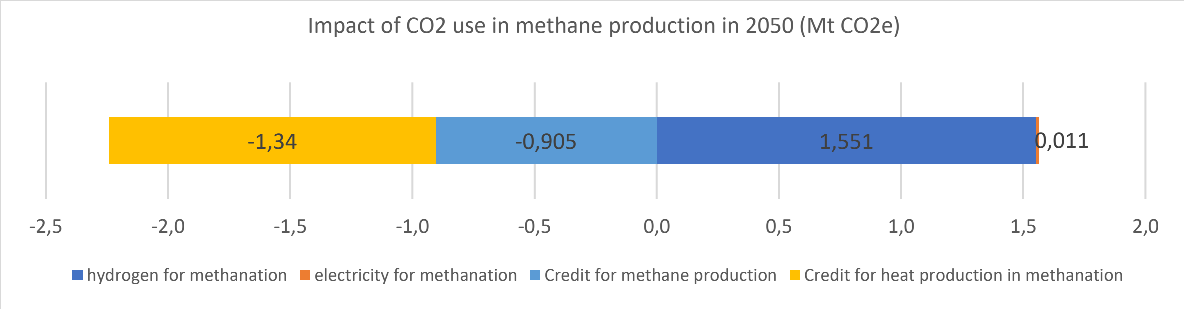

Figure 13: GWP impacts of CO_2 use in methanation reaction with renewable hydrogen.

This negative value of impact attributed to the outputs of methanation, relative to the credit for methane and heat production (avoided compared to the baseline situation), contributes to decrease the life cycle emissions to a lower net value as shown in Figure 14.

The most significant impact on GWP originates from the methane production process (blue column), and herein by the hydrogen production necessary for the reaction with carbon dioxide. The second most relevant impact on GWP is the amount of GHG emissions not retained by the carbon capture process (grey column). The rest of the impacts on GWP, relative to the carbon capture process GHG emissions (related mainly to infrastructure, electricity, and MEA life cycle emissions), conditioning (compression energy) and transport (pipeline and respective electricity use) are still identifiable but of secondary importance. The value for the storage process emissions is a negligible low value and it is not visible in the graph.

As stated above, the credit for the methane and heat outputs of the methanation process, allows to compensate a significant amount of the value chain GWP impact, represented by the declining and approaching zero value of the net GHG emissions represented in Figure 14 (purple line).

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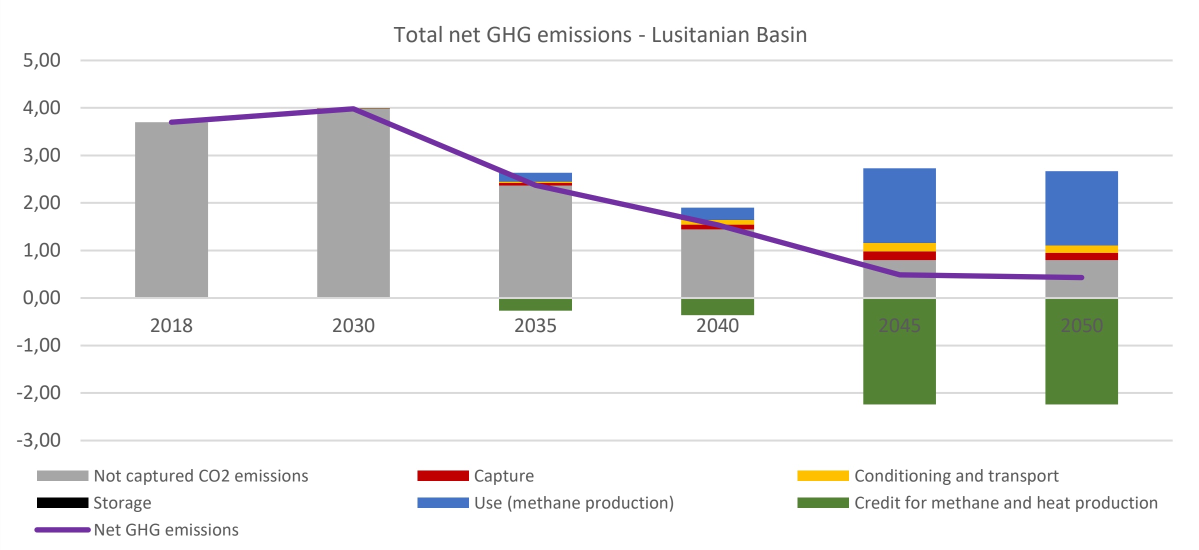

Figure 14: Total net GHG emissions between reference year 2018 and 2050 (intermediate years) in the main scenario (ON_Best) for the Lusitanian Basin.

Considering also the biogenic emissions, even though they have a GWP equal to zero, it is possible to show the total of captured CO_2, and the additional emissions associated with the carbon capture use and storage processes, as presented in

Table 16 and represented in Figure 15.

Table 16: Fossil and biogenic CO2 emissions captured and additional CCUS processes emissions

CO_2 emissions (Mt CO_2e/year)	2018	2030	2035	2040	2045	2050
Fossil CO_2 captured	0	0,079	2,768352	3,587	4,725	4,725
Bio CO_2 captured	0	0,013	0,513648	0,707	4,362	4,362
Fossil GHG emitted for CCUS	0	0,363	1,520	1,536	2,188	2,135
Bio CO_2 emitted for CCUS	0	0,051	0,238	0,269	1,751	1,751

Figure 15 shows the total of captured CO_2, as one highest column resulting of the sum of fossil (light orange) and biogenic (light green) carbon, and two lower columns for the non-captured CO_2 emissions. The non-captured biogenic CO_2 emissions (dark green), considered as having a GWP of zero, are represented separated from the non-captured fossil CO_2 emission (dark orange).

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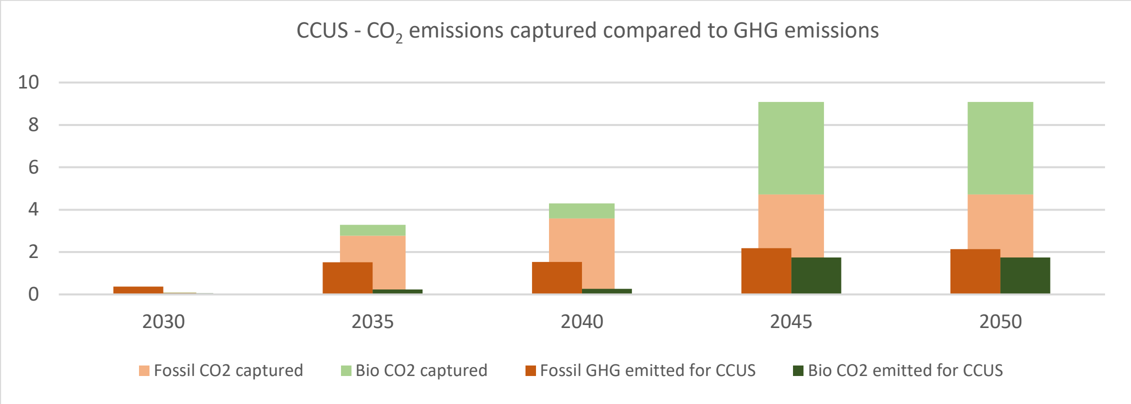

Figure 15: CO_2 emissions captured compared to GHG emissions induced by CCUS operation between 2026 and 2050.

Considering the significant positive and negative impacts of the CO_2 use by a methanation process, an alternative scenario of CCS (excluding biogenic CO_2 methanation) was analysed. This scenario includes a credit in the GWP impact category attributed to the biogenic CO_2 captured and sent to underground storage. The resulting graphical representation is shown in Figure 16. This analysis indicates that when considering exclusively the GWP impact category, the CCS scenario has a more favourable net GHG emissions balance when compared to the CCUS scenario previously shown. Due to the credit (negative values) of the storage of captured biogenic CO_2 emissions, the net GHG emissions balance (purple line in Figure 16), reaches a negative value in 2045, meaning that the set of emission facilities included in the analysis can be carbon negative and can positively contribute to the 2050 carbon neutrality goal.

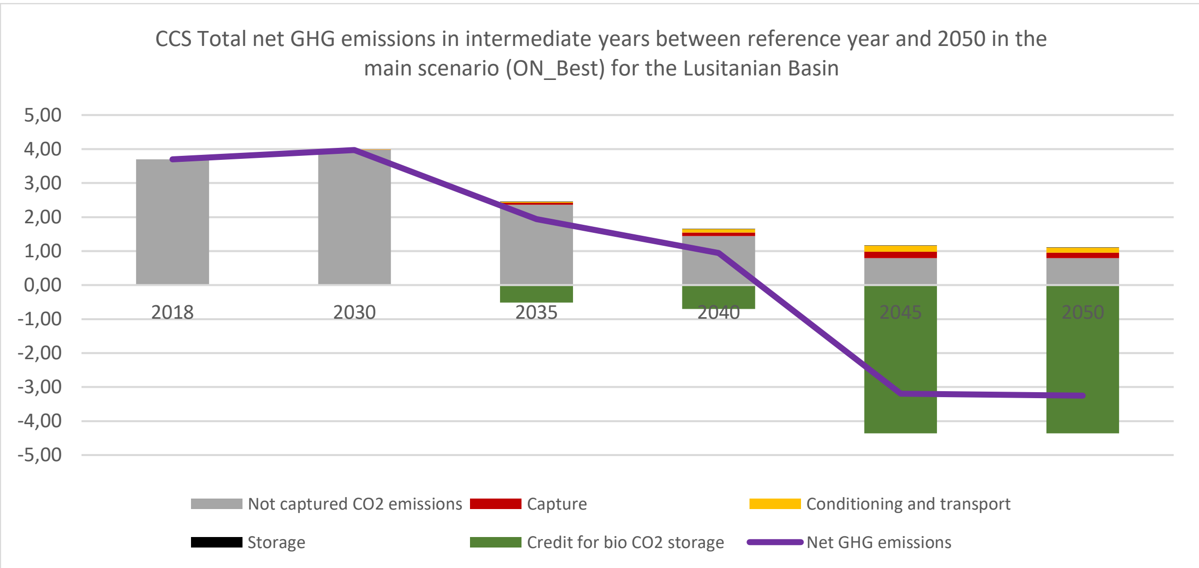

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Figure 16: Total net GHG emissions up to 2050 in the main scenario (ON_Best) without CO_2 use (methanation) for the Lusitanian Basin.

Representing biogenic captured CO_2 as negative emissions (credit for the storage of bio CO_2) in Figure 17, and considering that non-captured biogenic CO_2 emissions are climate neutral and thus not represented, and that captured and stored fossil (light orange) CO_2 is permanently stored, the remaining non-captured fossil CO_2 emissions (dark orange) have a much lower value than the biogenic (light green) column, resulting in an overall net negative GWP impact contributing to the 2050 carbon neutrality goal as stated above.

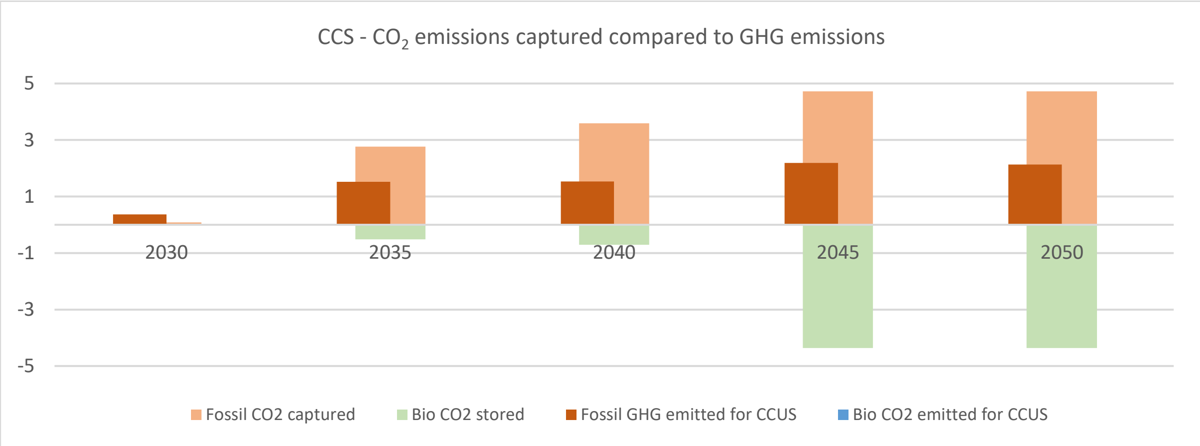

Figure 17: CO_2 emissions captured compared to GHG emissions induced by CCS operation between 2026 and 2050.

4.2.2.2 Cumulative Energy Demand

The cumulative energy demand (renewable and non-renewable) for the methanation process is shown in Figure 18. The inputs for the methanation (electricity and hydrogen) are positive energy demand values, and the outputs (methane and heat) are negative values representing a credit associated with the value-added gains. The balance of the positive and negative CED values is positive (9.59 GJ) and represents the net energy consumed in the production of 1 515 kton of methane, discounted by the energy content of methane and heat outputs.

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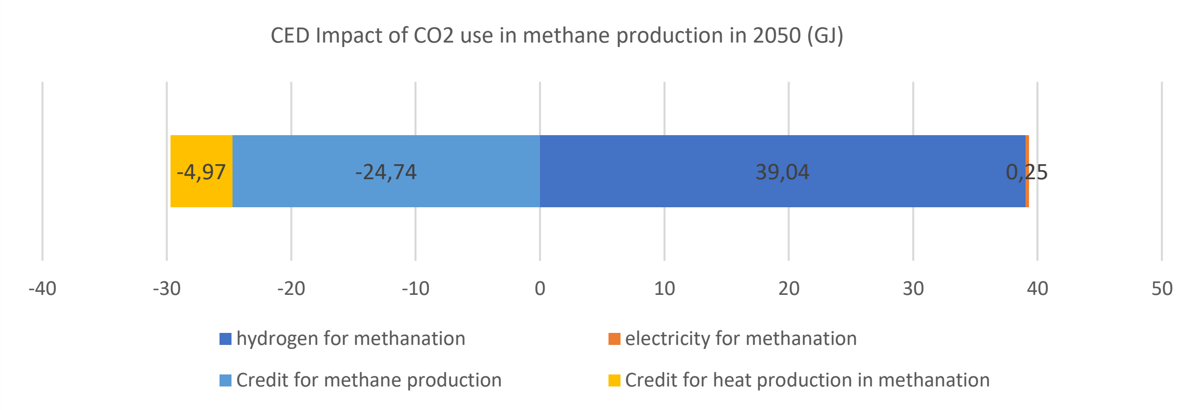

Figure 18: CED of the captured biogenic CO2 methanation process in 2050.

A comparison with the CED of the CCUS ON_BEST Lusitanian basin scenario up to 2050 is also presented in Figure 19. The values relative to the methanation process are a balance of CED positive and negative values of the methanation process, regarding the inputs and outputs of the process.

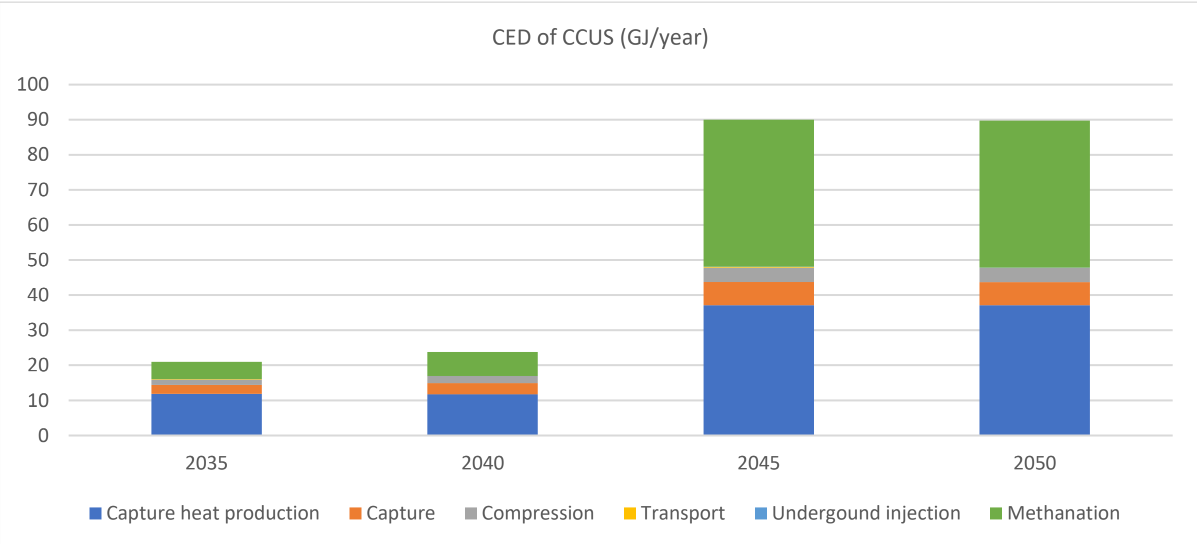

Figure 19: CED balance of the CCUS ON_BEST Lusitanian basin scenario up to 2050

As before, an alternative scenario of CCS (excluding biogenic CO_2 methanation) was analysed. This scenario includes the CED impact attributed to the biogenic CO_2 captured and sent to underground storage. The resulting graphical representation is shown in Figure 20. This analysis indicates that, considering exclusively the CED impact category, the CCS scenario has a more favourable net cumulative energy demand balance, a value of around half when compared to the CCUS scenario previously shown. In this case, the captured emissions are all (fossil and biogenic) sent to storage,

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and the energy use associated with compression, transport and storage is much lower than the energy used in the case of CCUS for the methane production.

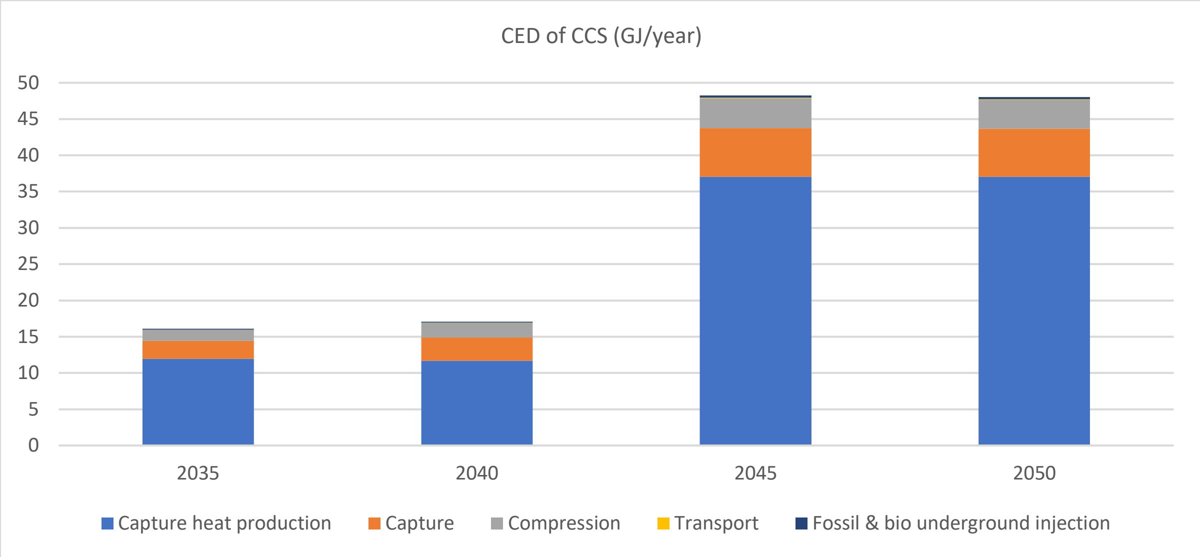

Figure 20: Total net CED impact up to 2050 in the main scenario (ON_Best) without CO_2 use (methanation) for the Lusitanian Basin.

The analysis of the life cycle impacts in the Lusitanian basin region didn't include the possibilities of process integration and industrial ecology, namely of the different possibilities of waste heat reuse in the emitter facilities or in neighbouring industries. All the processes of the emitter facilities in the Lusitanian basin region (cement, glass and pulp and paper with co-generation processes) have excess heat that could be used to supply at least an important part of the (heat) energy needs to the CO_2 capture processes (Biswas et al., 2020)(Hoppe et al., 2018). If integration and optimization of heat production and use is implemented in these processes it would encompass a significant reduction, at least up to 50%, of the emissions associated with the CO_2 capture process. Furthermore, in the CCUS scenario, the reuse of the methanation heat output could be integrated in the energy needs of the CO_2 capture processes and even more reduce the associated additional emissions. The quantification of this integration of processes considering the reuse of waste heat was not fulfilled in this analysis, but it is considered an area for future studies.

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4.2.3 Rhone Valley

4.2.3.1 Climate change

Main scenario

The net impact on climate change of the main CCUS scenario from 2020 (corresponding to the baseline situation) to 2050 is shown in Figure 21 for intermediate years. The year 2026 is represented as it corresponds to the start of capture on the steel plant. Figure 22 compares the amount of CO_2 captured to the GHG emissions induced by CCUS operation between 2026 and 2050, which can be interpreted as a GHG abatement efficiency (i.e. for 1 Mt CO_2 captured, x Mt CO_2eq. are re-emitted so the net GHG abatement is 1 – x Mt CO_2eq.).

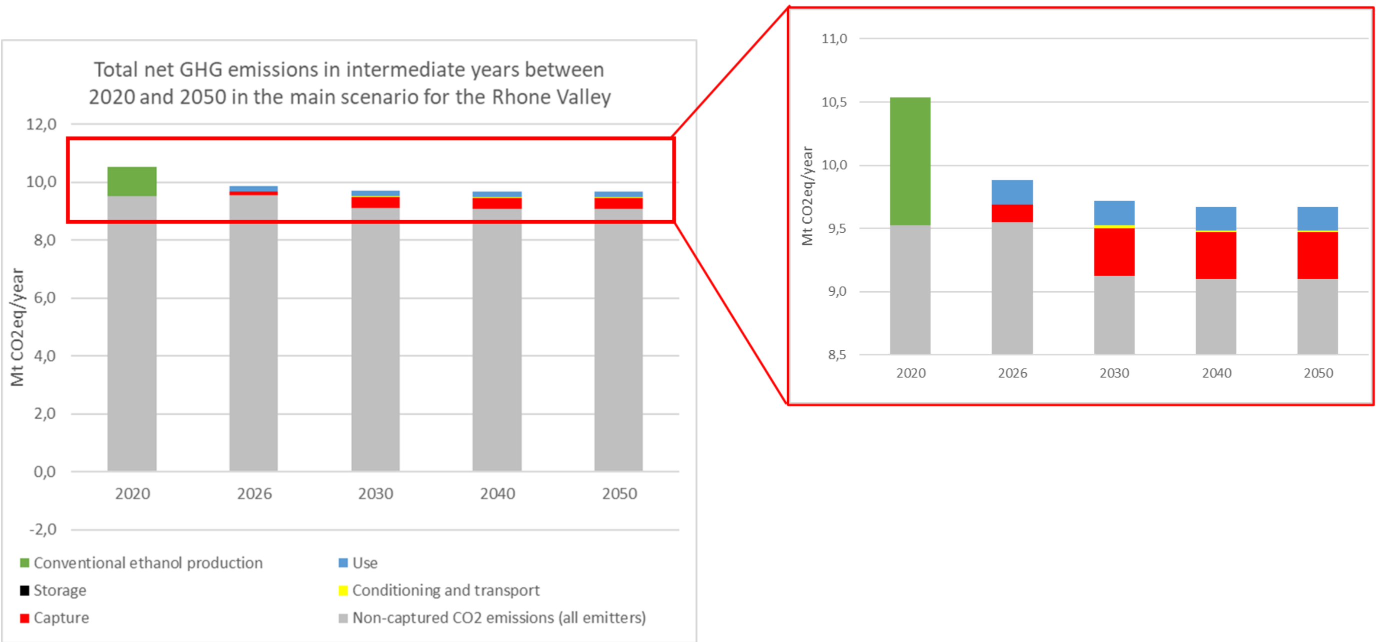

Figure 21: Total net GHG emissions between 2020 and 2050 (intermediate years) in the main scenario for the Rhône Valley.

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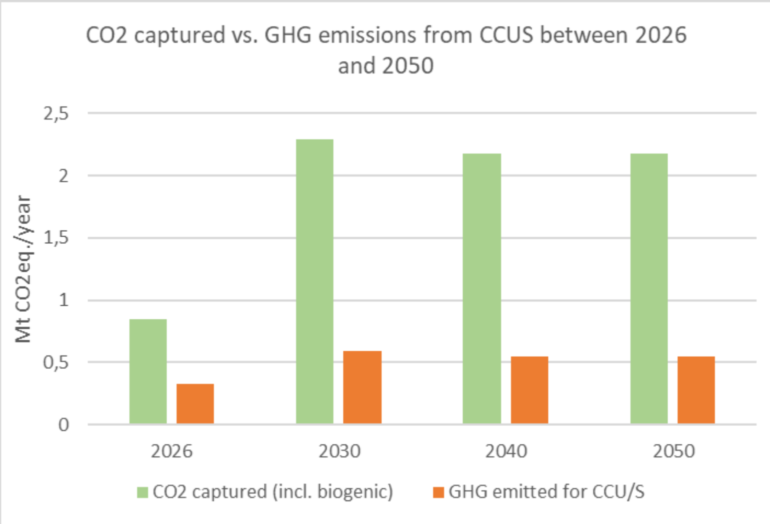

Figure 22: CO_2 emissions captured compared to GHG emissions induced by CCUS operation between 2026 and 2050.

Overall, the trend of the main scenario is a net decrease in GHG emissions associated to the selected emitters from 2026 to 2050, where a stabilized drop by 8.5% (i.e. - 0.9 Mt CO2eq./y) can be expected compared to 2020 (baseline situation).

The total net GHG emissions related to the **baseline situation** amount to **10.5 Mt CO_2eq./y**, of which 9.5 Mt CO_2eq./y correspond to the yearly CO_2 emissions of the regarded emitters without capture. Of this total, 7.5 Mt CO_2eq./y are emitted by the steel plant. The remaining 10% GHG emissions are due to the conventional ethanol supply to meet the demand before it is substituted by CO_2-derived ethanol in the CCUS scenarios. Impacts of conventional ethanol production mainly come from the ethylene feedstock production and heat consumption (see Figure 23).

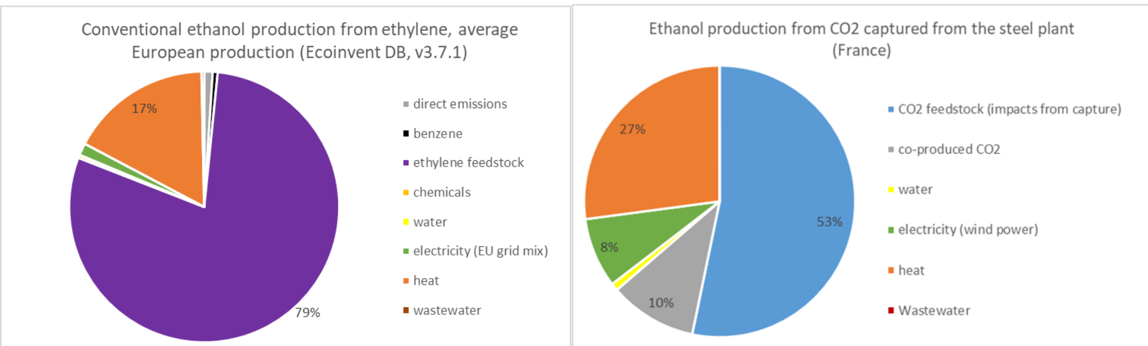

Figure 23: climate change impact contributions to conventional (left) and CO2-derived (right) ethanol production.

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From 2026 to 2029, with the implementation of the CCUS scenario and the launch of CO_2 capture applied to the steel plant, the net emissions are reduced by 0.6 Mt CO_2eq./y, corresponding to 0.842 Mt CO_2 captured yearly. This includes capture of additional emissions from the steel manufacturing process resulting from the internal energy provision for capture (captured at the same 10% rate as the direct CO_2 emissions, see section 3), which also means that the amount of non-captured emissions increases (as 90% of these additional emissions are released). Therefore, there remains a similar amount of yearly non-captured CO_2 emissions compared with the 2020 baseline. **Therefore, it is rather the substitution of conventional ethanol supply that induces a benefit**. GHG emissions of the capture process arise from the upstream impact of natural gas supply for heat production, and from the fraction of non-captured CO_2 due to the capture process efficiency (90%). Finally, ethanol production from CO_2 implies indirect GHG emissions because of the required heat and electricity (to a lesser extent as it is sourced from wind power, see Figure 23), and direct GHG emissions because of the co-produced CO_2 stream.

From 2030 to 2039, an additional amount of 1.45 Mt CO_2 is captured each year on the other emitters (hydrogen, cement, chemicals plants and the refinery) and sent to the storage site, which enables a net GHG emission decrease of 0.2 Mt CO2eq./y compared to the previous 2026-2029 period. For each Mt CO_2 captured, 0.26 Mt CO_2eq. are emitted (see Figure 22), again mostly due to the capture and ethanol production processes. However, capture on the chemicals (low emissions level and capture rate of 20%) and hydrogen plants (low emissions level despite 80% capture rate) neither represent a high share of the CO_2 captured, nor of the induced GHG emissions. Capture on the cement plant remains interesting though it is neither a big emitter.

Conversely, the conditioning, transport and storage stages have a negligible contribution to the generated GHG emissions. On Figure 24 where details per emitter are provided for the example year 2030, it can be seen that conditioning (gaseous CO_2 compression, or liquefaction) is the most GHG intensive stage, because of the electricity consumed. Transport and storage both involve a very small electricity consumption (recompression over the pipeline, injection in the storage site) and few direct emissions (slight CO_2 leakage through pipeline transport, see section 3.2.3).

Overall, the influence of switching the prospective electricity mix selected for 2050 (50% nuclear or 100% renewables, see section 3.5.3) is insignificant regarding the total contribution of electricity-consuming stages to the total climate change impact.

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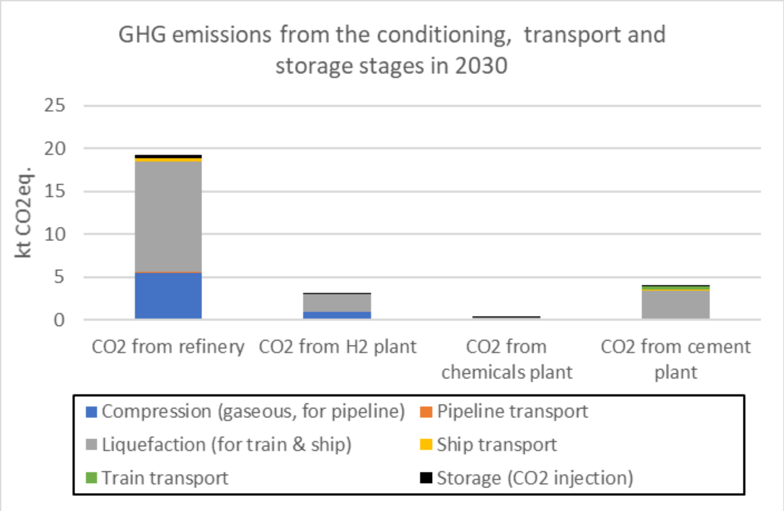

Figure 24: Detail of GHG emissions (in kt CO_2eq./y) related to the conditioning, transport and storage of CO_2 in 2030.

Finally, **from 2040 to 2050,** where capture on the hydrogen plant stops and capture on the waste-to-energy starts, net GHG emissions are slightly affected and remain stable compared to the previous 2030-2039 period (0.1 Mt CO2eq./y less emitted). 2.18 Mt CO_2/y are captured, while 0.54 Mt CO2eq./y are released due to CCUS (see Figure 22). The relative impact contributions between capture, conditioning, transport and storage stages remain similar. Finally, storing the share of biogenic CO_2 captured on the waste-to-energy plant (56%, see section 2.3.3) implies negative emissions of -0.03 Mt CO_2eq./y, which does not enable a significative offset compared to the total generated GHG emissions.

As a summary, Table 17 shows the **cumulative GHG emissions from 2020 to 2050 in the main scenario**, compared to those that would occur in the baseline scenario (i.e. no CCUS from 2020 to 2050). The total amount of CO_2 captured within this period is also indicated, so as to highlight the net GHG abatement potential of the main scenario. Indeed, **between 2026 and 2050, 50.2 Mt CO_2 can be captured, used or stored implying GHG emissions of 13.3 Mt CO2eq., which can be understood as a 74% GHG emission saving when operating CCUS**. Then the total GHG emissions of the main scenario (i.e. CCUS-related + non-captured direct emissions + emissions from the conventional ethanol supply until it is substituted by CO_2-derived ethanol) amount to 306 Mt CO_2eq., meaning a **6% reduction compared to the total baseline GHG emissions** of 325 Mt CO_2eq.

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Table 17: Cumulative GHG emissions in the main scenario for the Rhône Valley versus the baseline scenario

CUMULATIVE EMISSIONS IN THE MAIN SCENARIO					
Mt CO2eq.	**TOTAL**	**of which remaining, non-captured CO2 emissions**	**of which emissions from conventional ethanol production**	**of which emissions from capture, conditioning, transport, use/storage**	**Total CO2 captured**
2020 to 2025	63.2	57.1	6.1	-	-
2026 to 2029	39.5	38.2	-	1.3	3.4
2030 to 2039	97.2	91.2	-	5.9	22.9
2040 to 2050	106.1	100.1	-	6.0	24.0
TOTAL	306.0	286.7	6.1	13.3	50.2
share		94%	2,0%	4,3%	
CUMULATIVE EMISSIONS IN THE BASELINE SCENARIO, i.e. no CCUS from 2020 to 2050					
Mt CO2eq.	**TOTAL**	**of which direct, non-captured CO2 emissions**	**of which emissions from conventional ethanol production**		
2020 to 2050	324.6	293.3	31.3		
share		90%	10%		

Altnative scenario In the alternative scenario, only the conditioning, transport and storage stages are modified from 2030 to 2039 as CO_2 is directly sent to the Paris basin storage site from 2030 (see section 2.3.3). Considering the share of GHG emissions these stages represent in the main scenario from 2040 to 2050 (corresponding to storage in the Paris basin as well, see Figure 21), **the absolute results, trends and conclusions regarding the GHG emissions in the alternative scenario remain the same as for the main scenario**. **From an environmental point of view, selecting this alternative**

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scenario neither implies benefits nor drawbacks. Thus results are not depicted for the sake of simplification.

4.2.3.2 Cumulative Energy Demand (CED)

Main scenario

The CED (renewable and non-renewable) of the main scenario in intermediate years from 2020 to 2050 is shown in Figure 25. A comparison to the CED of the baseline scenario summed from 2020 to 2050 is also depicted in Figure 26. The CED in the baseline scenario corresponds to the conventional ethanol supply.

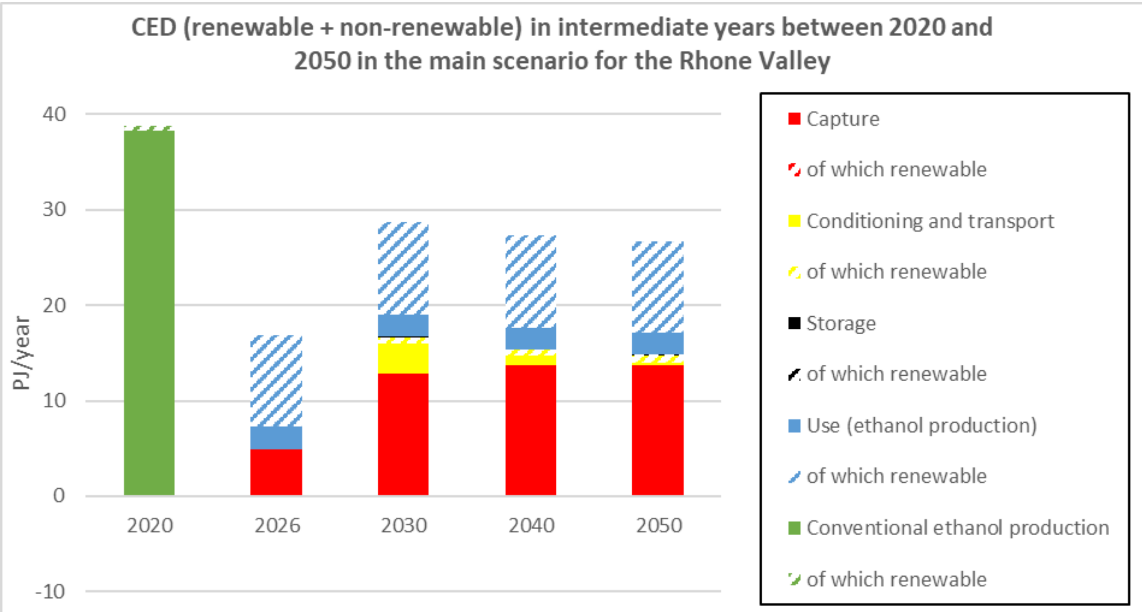

Figure 25: cumulative energy demand (CED) between 2020 and 2050 for intermediate years in the main scenario for the Rhône Valley. CO_2-derived ethanol produced with 100% renewable energy (wind power) from 2026 to 2050.

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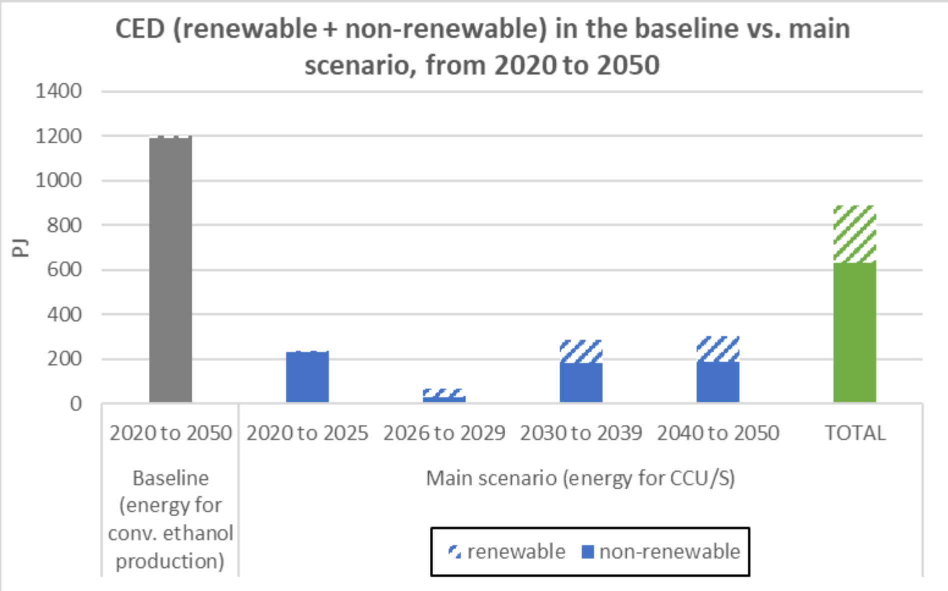

Figure 26: cumulative energy demand (CED) between 2020 and 2050 (+ intermediate years) in the baseline and main scenarios for the Rhône Valley. CO_2-derived ethanol produced with 100% renewable energy (wind power) from 2026 to 2050.

Overall, the implementation of the main CCUS scenario between 2020 and 2050 (knowing that the first capture process starts in 2026) is 26% less energy demanding than the baseline situation without CCUS over the same period. This is an encouraging result as the capture stage in particular is very energy-demanding, as it is the case when transforming CO_2 into ethanol. Again, though compressing or liquefying CO_2 requires energy, the conditioning and transport stage remain the smallest contributor to this indicator as was the case with the climate change indicator. Moreover, the non-renewable energy share in the CCUS scenario represents between 40% (2026) and 60% (2030 to 2050), mostly because of the assumptions of CO_2-derived ethanol production being based on renewable electricity (see section 3.4.1), and of energy for capture being supplied with natural gas until 2050 for most of the emitters (see section 3.1). The latter assumption could actually be reviewed to account for the expectable progressive substitution of such a fossil feedstock with e.g. biogas in France. Therefore, the non-renewable energy demand of the CCUS scenario may be overestimated.

Regarding conventional ethanol production in the baseline situation, an evolution of the energy mix could also be accounted for (remaining the same from 2020 to 2050 in this study). However, the total CED in this baseline scenario remains higher than the CED in the CCUS scenario, which means that **a smaller share of global energy production (from both renewable and non-renewable sources) would have to be dedicated to the intended CCUS value chains than to conventional ethanol production anyway.**

Sensitivity to the electricity source used for ethanol production from CO_2

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Whether ethanol can be produced with a fully renewable energy source (here wind power) from 2026 is a questionable assumption. Therefore, the following Figure 27 and Figure 28 show the CED obtained when considering the national electricity grid mix for ethanol production, still evolving to a 100% renewable mix in 2050.

In this case, the CED of the whole CCUS value chains in 2050 is similar to what was found with a 100% wind power consumption for ethanol production, however the CED related to this utilization phase progressively decreases from 28/y PJ in 2026 to 13/y PJ in 2050 (see Figure 27). Using wind power this CED amounts to 12 PJ/y (see Figure 25). Summing up the CED of the CCUS scenario from 2020 to 2050, it is barely smaller than the CED of the baseline scenario (see Figure 28). **This result encourages increasing the share of renewable energy for ethanol production as soon as possible. Combined to an incorporation of renewable energy for capture needs, the CED of the CCUS scenario could even more decrease compared to the baseline scenario.**

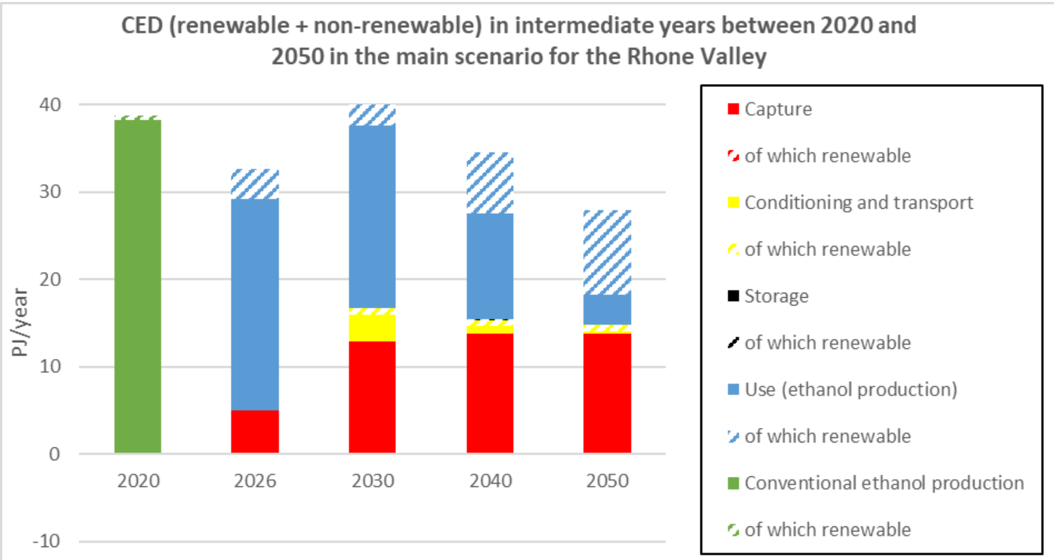

Figure 27: cumulative energy demand (CED) between 2020 and 2050 for intermediate years in the main scenario for the Rhône Valley. CO_2-derived ethanol produced with the national grid mix from 2026 to 2050 (100% renewable).

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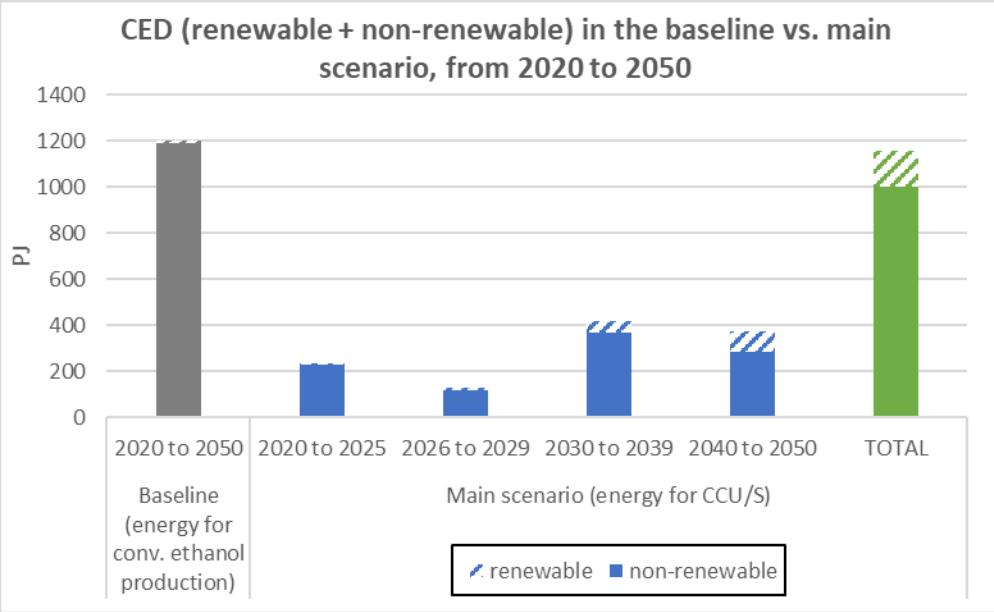

Figure 28: cumulative energy demand (CED) between 2020 and 2050 (+ intermediate years) in the baseline and main scenarios for the Rhône Valley. CO_2-derived ethanol produced with the national grid mix from 2026 to 2050 (100% renewable).

Finally, a transition to the 50% nuclear mix described in RTE's prospective work (see section 3.5.3) would yield mitigated results in terms of CED for the CCUS scenario, as this prospective mix has a CED of 2.6 MJ/MJ el. (including 2 MJ non-renewable energy due to the nuclear share) compared to 1.2 for the 100% renewable prospective mix.

Altnative scenario

As was the case with the climate change indicator, the CED of the alternative scenario is sensibly the same as in the main scenario, because the differing stage between both scenarios, i.e. the transport stage, only makes a difference between 2030 and 2039. Therefore, in the alternative scenario, the CED related to the conditioning and transport stage from 2030 and 2039 would be around the 2040 level of the main scenario (which corresponds to the situation of the alternative scenario from 2030).

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5 Discussion

5.1 Main outcomes

In the three regions assessed, the implementation of the CCUS scenarios enables net GHG savings compared to the baseline situation. Capture process-related impacts (mainly because of energy provision, both through the upstream impacts of additional fossil-based fuel supply and the related combustion GHG emissions) are the most critical contributor to generated GHG emissions, while the conditioning and transport chains globally bear insignificant impact contributions.

The storage stage mainly involves a low electricity consumption for injection whose impact is negligible; moreover, the storage of biogenic CO_2 implies negative emissions which are determinant in the global GHG balance of the Lusitanian basin scenario, where mainly biogenic CO_2 can be captured and stored enabling net negative emissions. In the Rhône valley the proportion of biogenic CO_2 captured and stored is not significant enough. In that sense, the Ebro basin situation is similar to that of the Rhône Valley because the proportion of biogenic CO_2 captured and stored is not significant enough.

Finally, the impacts of CO_2 utilization really depend on the final use of CO_2 and on the transformation process settings (e.g. renewable power consumption for energy needs). However, the comparison of CCU impacts to those of the substituted conventional products supply and use (occurring in the baseline system) is mostly favourable to CCU as the climate change impact of conventional products is generally bigger.

In each region, the capture rate and energy consumption for capture combined to the intensity of yearly CO_2 emissions of the emitters are found to be determining parameters of the GHG reduction efficiency of the CCUS scenarios. The base assumptions in each CCUS scenario play a key role regarding the LCA outcomes in terms of CCUS climate benefits. Therefore, process integration in the value chain would be decisive to optimize net GHG emissions related to CCUS, for instance whether waste heat is recoverable in some plants to cover capture energy needs. However, CCUS definitely appears useful to succeed in the GHG emission reduction in the considered regions, especially through the combination of storage and utilization when few biogenic CO_2 can be captured and stored (thereby generating beneficial negative emissions).

Regarding cumulative energy demand when implementing the CCUS scenarios, results show that the use of renewable energy for both capture and utilization energy requirements is to be foreseen as soon as possible to efficiently decrease the CED (both renewable and non-renewable) compared to the current situations. Most utilization pathways require hydrogen (methanation, ethanol and methanol production) whose production through electrolysis is energy-intensive, so the relevance of green hydrogen is definitely proven both in terms of GHG emissions and CED reductions.

Table 18 summarizes the key outcomes of the LCA of CCUS scenarios in the three assessed regions.

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Table 18: summary of key outcomes of the study in the three regions.

<table>
<tr><th></th><th>Capture</th><th>Conditioning & transport</th><th>Storage</th><th>Utilization</th></tr>
<tr><td>Ebro basin</td><td rowspan="3">Energy for capture penalizing GHG emissions and CED scores for the biggest emitters
➔ Heat recovery where feasible?
➔ Incorporate more renewable energy</td><td rowspan="3">insignificant impact contributions (GHG and CED)</td><td>CO_2 storage generates lower emissions than capture, and efficiently lowers direct CO_2 emissions of the emitters</td><td>Low climate impact of methanol production (for chemical industry) compared with conventional global methanol production</td></tr>
<tr><td>Lusitanian basin</td><td>Storing biogenic CO_2 is highly beneficial (net negative emissions over 1 year)</td><td>Methanation involves slightly lower impacts than conventional methane production</td></tr>
<tr><td>Rhône Valley</td><td>CO_2 storage generates and avoids few impacts, but efficiently lowers direct CO_2 emissions of the emitters</td><td>Ethanol production (for plastic) saves impacts compared to conventional ethanol production</td></tr>
</table>

5.2 Limits of the studies

Several limitations in this study can be outlined, especially related to a lack of data and the generic modelling approach.

Firstly, the CCUS chains modelled remain generic in terms of data used to model capture, transport and utilization. Inventory data is sourced from the literature, trying to be as representative as possible of the actual emitters regarding their nature (power plant, cement plant etc.) and dimensions (order of magnitude of power/product output etc.). For some emitters inventory was approximated with data on capture for other emitters (see e.g. section 3.1.7), however inputs and

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outputs are expected to be similar whatever the emitter is quoted in the literature survey used for this study (for instance the amount of MEA make-up is similar for several types of emitters). Although many inputs and outputs have a low or even insignificant climate change impact contributions, they may be more critical in other impact categories, which were not assessed here (e.g. human toxicity, air pollution…). Finally, data on other direct emissions than CO_2 at the exhaust of the emitters was also missing (e.g. NOx, SOx…) but these should remain the same between the baseline and CCUS scenarios, so they would not have been a key source of impact difference (whatever the impact category) between both scenarios.

GHG emissions and CED are strongly impacted by the required energy for capture (amount and fuel source) which also derives from generic literature data used in WP5. A sensitivity analysis (e.g. ±20% consumption) could be performed on this parameter. Also, the assumption of capturing energy-related CO_2 emissions at the same capture rate as direct CO_2 emissions is questionable and plays a big role in energy-related GHG emissions, because of the share of non-captured CO_2. This simplification – which was necessary regarding the project magnitude – could be reviewed as the feasibility of capturing those emissions at a similar capture rate is not proven (for instance if CO_2 from the energy generation unit is more diluted).

Finally, additional prospective assumptions could be taken beside the evolution of the national electricity mixes, which was the only activity for which consolidated prospective scenarios were available (see section 3.5). Such assumptions on other parameters or activities were more difficult to find and it would have been time consuming, while increasing uncertainties in the modelling. However, the sensitivity of the results to the energy supply mix and amount for capture or for conventional products in the baseline scenarios could be tested for instance. Moreover, additional information on decarbonization roadmaps may be available for some emitters, which should be taken into account instead of considering constant yearly emissions and capture rates. For instance ArcelorMittal in the Rhône Valley intends to operate on several other levers to reduce their CO_2 emissions within 2050 besides CCU (e.g. steel recycling, ore reduction process improvements) which would decrease the total yearly emissions. Such information was communicated to us while finalizing the present report, which did not enable to update the LCA accordingly.

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6 Conclusion

In the three regions assessed, the implementation of the CCUS scenarios enables net GHG and CED savings compared to the baseline situation from 2020 to 2050 according to the performed LCAs. Capture process-related impacts (mainly because of energy provision, both through the upstream impacts of additional fuel supply and the related fuel combustion GHG emissions) are the most critical contributor to generated GHG emissions and significantly to CED, while the conditioning and transport chains globally bear insignificant impact contributions. The storage stage mainly involves a low electricity consumption for injection whose impact is negligible; moreover, the storage of biogenic CO_2 occurring in some regions implies negative emissions which are determinant in the global GHG balance in the Lusitanian basin, while negligible in the Rhône Valley. Finally, the impacts of CO_2 utilization strongly depend on the final use of CO_2 and on the transformation process settings (e.g. renewable power consumption for energy needs). However, the comparison of CCU impacts to those of the substituted conventional products supply and use (occurring in the baseline system) is mostly favourable to CCU, even though no prospective assumptions on potential conventional process evolutions were taken. The CED analysis also highlighted the relevance of switching to renewable energy sources as soon as possible which helps decrease both the non-renewable and total energy demands.

In each case, the capture rate and energy consumption for capture, combined to the intensity of yearly CO_2 emissions of the emitters, are found to be determining parameters of the GHG reduction efficiency of the CCUS scenarios. The base assumptions in each CCUS scenario (capture rate, energy for capture, conventional products substituted by utilization pathways) play a key role regarding the LCA outcomes in terms of CCUS benefits. The analysis of the life cycle impacts didn't include the possibilities of process integration and industrial ecology, namely of the different possibilities of waste heat reuse in the emitter facilities or in neighbouring industries. All the emitter facilities that have excess heat should use it to supply at least an important part of the heat energy needs to the CO_2 capture processes. If integration and optimization of heat production and use is implemented in these processes it would encompass a significant reduction of the emissions associated with the CO_2 capture process. For instance, in the CCUS scenario for the Lusitanian basin the reuse of the methanation heat output could be integrated in the energy needs of the CO_2 capture processes and reduce even further the associated additional emissions. The quantification of this integration of processes considering the reuse of waste heat was not fulfilled in this study, but it is considered an area for future studies. Finally, this study could be refined whether prospective insights on other activities than the national electricity mixes could be derived and accounted for in the modelling.

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7 Reference List

An, J., Middleton, R. S. & Li, Y., 2019. Environmental Performance Analysis of Cement Production with CO2 Capture and Storage Technology in a Life-Cycle Perspective. *Sustainability.*

Antonini, C. et al., 2020. Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis. *Sustainable Energy & Fuels,* Volume 4.

Chisalita, D.-A.et al., 2018. Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology. *Journal of cleaner production.*

Coussy, P., 2021. Deliverable D5.2: Description of CCUS business cases in eight southern European regions, 133p. EU H2020 STRATEGY CCUS. Project 837754 Report , s.l.: s.n.

Fadeyi, S., Arafat, H. A. & Abu-Zahraa, M. R., 2013. Life cycle assessment of natural gas combined cycle integrated with CO2 post combustion capture using chemical solvent. *International Journal of Greenhouse Gas Control,* Volume 19, pp. 441-452.

Giordano, L., Roizard, D. & Favre, E., 2018. Life cycle assessment of post-combustion CO2 capture: A comparison between membrane separation and chemical absorption processes. *International Journal of Greenhouse Gas Control,* Volume 68, pp. 146-163.

Hischier, R. et al., 2010. Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.2., Dübendorf: s.n.

IPCC, 2013. Climate Change 2013. The Physical Science Basis. Working Group I contribution to the Fifth Assessment Report of the IPCC, s.l.: s.n.

JRC, 2020. JEC Well-to-Tank report v5 - Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, s.l.: s.n.

Koornneef, J., Keulen, T., Faaij, A. & Turkenburg, W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2. *International Journal of Greenhouse Gas Control,* 2(4), pp. 448-467.

Markewitz, P. et al., 2019. Carbon Capture for CO2 Emission Reduction in the Cement Industry in Germany. *Energies,* 12(12).

Singh, B., Strømman, A. H. & Hertwich, E. G., 2011. Comparative life cycle environmental assessment of CCS technologies. *International Journal of Greenhouse Gas Control,* 5(4), pp. 911-921.

Thonemann, N. & Pizzol, M., 2019. Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry. *Energy & Environmental Science,* Volume 12.

van der Giesen, C. et al., 2017. A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO2 versus MEA-Based Postcombustion Capture. *Environmental Science & Technology.*

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

Young, B. et al., 2019. Comparative environmental life cycle assessment of carbon capture for petroleum refining, ammonia production, and thermoelectric power generation in the United States. *International Journal of Greenhouse Gas Control,* Volume 91.

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