Identification of sustainable cooperation schemes in regional CCS systems

Portugal case study: Break-even CO_2 prices for CCS adoption

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Thanes PETER is a current Energy & Markets student at the IFP School and an apprentice at the IFPEN research center. Prior to this, he earned a master's degree in chemical engineering from ENSIC, with a focus on advanced process engineering. Thanes had gone through a plethora of experiences and learned a lot throughout this journey, from creating a 3D micro-heat exchanger to adapting a cost estimation software for Axens, which helped him to hone and cultivate newly learned knowledge and skills. His work at IFPEN revolves around research and analysis of both non-renewable and renewable energy markets, aligning with his vision of acknowledging the importance of renewable energy and the urgency to take action against climate change. His interest lies in learning how the world works from an economic point of view and deepening his knowledge of the current climate movement.

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Prof. Massol is a founding member and serves as the Executive Director of the Chair “The Economics of Gas”, a research and teaching initiative associating IFP School, Mines ParisTech, University Paris-Dauphine and Toulouse School of Economics. He is also Head of the Energy Transitions research initiative at the “Climate Economics Chair” and contributes to the IFP School's Chair "Carbon Management and Negative CO_2 emissions technologies towards a low carbon future" (CarMa). Olivier is an elected council member of the French Association for Energy Economics.

Prof. Massol’s research interests and expertise are in applied economics and more specifically in the fields of Industrial Organization and Energy and Natural Resources Economics. His publications have appeared in top-field journals including The Energy Journal, Energy Economics, Energy Policy, the European Journal of Operations Research or Resources and Energy Economics. His contributions concentrate on questions related to: (i) the monetization of natural resources; (ii) the economics of energy infrastructures and emerging energy technologies; (iii) the modelling of strategic interactions in the energy industries, or (iv) the spatial integration of energy markets. His research mobilizes a variety of quantitative techniques drawn from game theory, econometrics, and operations research.

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1 Executive summary

This report examines the conditions enabling the deployment of large-scale pipeline and storage infrastructure needed for the capture of CO_2 in Portugal by 2050. It describes a modelling approach for determining the least-cost infrastructure for connecting a geographically disaggregated set of emitting and storage clusters, as well as the CO_2 price thresholds required to ensure that the agents considered make the necessary investment decisions and share a common infrastructure.[1] This framework is used to assess the relevance of various policy scenarios, including (i) the perimeter of the targeted emitters for CCS uptake and (ii) the relevance of constructing several regional networks instead of a single grid to account for the spatial characteristics of the Portuguese region. We find that one single network naturally emerges in the centre of Portugal. The presence of separability in the system implies the possibility of separating two subsystems that share the same storage site. Because these subsystems may be deployed independently, governments do not need to focus their efforts on building a large-scale national infrastructure; instead, a regional approach to CCS implementation is preferable. Cost-engineering analyses based on average cost assumptions may understate the exact break-even price. The high capture costs of certain emitters have a direct impact on determining the price for CCS infrastructure adoption. These clusters with large CO_2 costs relative to their low annual CO_2 emissions are the least attractive candidates to be included in the potential coalition for CCUS adoption. The policy implications of these findings concern the elaboration of relevant, pragmatic recommendations to envisage CCS deployment locally, focusing on emitters with lower CO_2 capture cost options. The similar approach was used in approach to storage, where only onshore sites were looked upon due to significantly lower levelized storage costs. However, despite the significant higher cost, they could potentially find easier acceptance in terms of public opinion and therefore prevail over onshore storage as a final choice. It could also provide a higher storage scale. Public funding of the offshore storage solution could bring the required investments to a more acceptable level.

It is important to point out that this approach do not consider CO_2 utilisation options evaluated in the economic scenarios presented in deliverables 5.2 (Description of CCUS business cases) and 5.3 (Economic Evaluation of scenarios). The utilisation scenarios may have significant impact on the economics and decision making of the emitters as they will provide economic benefit for the emitters and may, therefore, reduce the overall capture and storage costs. Moreover, in CCS the development of infrastructures is led by the location of CO_2 sources and of geological formations whilst in CCU major industrial clusters would need to be taken into an account, as they can use the captured CO_2 as a feedstock for the manufacturing of other products. Therefore, some of these CO_2 utilisation clusters could be a game-changer as those solutions might be preferred to geological storage ones alone. Above said is particularly relevant for the methanation using CO_2 from the bioenergy as well as pulp and paper producing industries, but also to some extent for the cement one.

It should also be stated that government can play significant role in making the CCUS chains happen (e.g., through providing funding, simplifying permitting, providing risk guaranties, working with public acceptance, etc.) that would be used by several sectors. The EU Guidelines on State aid for climate, environmental protection and energy provide guidance on how the Commission will assess the compatibility of environmental protection, including climate protection, and energy aid measures which are subject to the notification requirement under Article 107(3), point (c), of the Treaty. In our opinion State Aid funding aiming at decreasing the initial private investment for deployment of large-scale pipeline and storage infrastructure and therefore the investment hurdles required for the implementation of these CCUS technologies and the capture of CO_2 in Portugal by 2050 should be further considered in the decision process following StrategyCCUS project.

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[1] *These conditions are derived from the cooperative game theoretic analysis in Massol et al. (2015) and are identical to the ones needed for a project whereby the provision of CO_2 transportation is controlled by an independent pipeline operator (see Massol et al., 2015).*

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2 Introduction

CCS is widely recognized as a critical technology in long-term energy scenarios (e.g., IEA, 2017, IEA, 2021; Knopf et al., 2013) because it successfully reconciles existing reliance on fossil fuels with lofty CO_2 abatement objectives necessary for a 2°C-compatible future. CCS, on the other hand, is seeing a slower-than-anticipated adoption rate. In light of this challenge, research on the socio-economic hurdles to CCS deployment and recommendations for legislative solutions is gaining traction. Bearing in mind these difficulties, research on the socioeconomic barriers to CCS deployment and legislative proposals is gaining pace.

A critical question for policymakers remains unanswered, and this report's core goal is to answer it, based on the example of the Portuguese cluster: what is the market price per ton of CO_2 that would be required to drive the adoption of CCS capabilities? Until now, CO_2 infrastructure issues have primarily been investigated using optimization techniques to determine the most cost-effective design of an integrated CCS infrastructure network. However, the models used in these previous studies assume an idealized industrial organization in which a single decision-maker (e.g., a benevolent central planner) has total control over the whole CCS chain. However, the development of a large-scale CCS infrastructure depends on individual decisions by a group of independent emitters to adopt carbon capture capabilities. Because these emitters are unlikely to mindlessly obey the commands of a "superior" decision-maker, a deeper look at the coordination problems that this group of autonomous agents faces is required. To address this issue, a research effort conducted at IFP School during the last decade has resulted in a series of methodological contributions (Massol et al., 2015) that use a cooperative game theoretic approach to investigate the conditions required for a group of emitters to share a common pipeline infrastructure and calculate the CCS adoption break-even price.

The purpose of this research report is to examine the conditions which are required for enabling the deployment of a large-scale CO_2 infrastructure project aimed at transporting CO_2 emissions captured at a series of industrial clusters to a series of pre-identified storage sites where the CO_2 could be injected for permanent storage using these innovative approaches rooted in theoretical economics. The analysis will allow us to assess the viability of a certain CCS infrastructure and provide insight into the coordination challenges that may arise.

We consider Portugal as a case study for our analysis because at least three distinct lines of arguments make it an interesting candidate. First, Portugal laid out a road to carbon neutrality and defined the policies and initiatives that will be needed to get there, titled "Roadmap for Carbon Neutrality 2050 (RCN2050): Long-term Strategy for Carbon Neutrality of the Portuguese Economy by 2050. It explains that achieving carbon neutrality is both economically and technologically feasible, and that it is based on reducing emissions by 85% to 90% by 2050 compared to 2005, and offsetting remaining emissions by ensuring a total carbon sequestration capacity of around 13 million tonnes by 2050 in agriculture and forestry. Emission reductions of 45%-55% are expected by 2030, and 65%-75% by 2040, according to the trajectory.

Second, geography and spatial considerations cannot be overlooked. While the North Sea oil fields are recurrently presented as a preferred destination for storing the CO_2 captured in Europe, the cost of routing the CO_2 captured in Portugal to the trunkline systems envisioned in northern Europe would be prohibitive.[2] Meanwhile, huge offshore storage sites in Portugal might provide a better alternative to the prior ones.

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[2] *Oei et al. (2014) formulate an infrastructure planning model aimed at determining the least costly deployment of a European CCS infrastructure. According to their simulation results (see Oei et al., 2014 – figures 5 to 8), nations like Spain and Portugal should favour the deployment of an Iberian-centric CCS infrastructure that would remain physically disconnected from the northern European CO2 pipeline systems.*

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Third, a remarkable data set on emission sources and storage potentials[3] has recently been assembled for that country under the auspices of work package 2 (Mapping technical aspects) of the STRATEGY CCUS project.

The following is a breakdown of the paper's structure. The instance of Portugal is presented in Section 3. Section 4 explains how to find the most cost-effective CCS infrastructure and suggests two regional subsystems that might be installed separately in Portugal. Section 5 is a methodological section that illustrates how cooperative game-theoretic conceptions may be used to identify the prerequisites for CCS adoption. Section 6 summarizes our results on the break-even pricing for the deployment of the several suggested subsystems. Our conclusion is outlined in the last part, which also highlights the policy implications of our research. Appendix A contains the exact numerical assumptions we used in our investigation. Appendix B has a full description of the optimization model that was utilized to assist our research.

3 Case Study Description: Sources of CO_2 in Portugal and potential sinks

In this section, we first describe the situation of CCS in Portugal, in terms of the spatial distribution of emission clusters and storage sites, and the techno-economic characteristics of transport and storage technologies.

3.1 The emission clusters under scrutiny

A set of 13 large facilities that are currently emitting CO_2 in mainland Portugal in 2021 were selected for evaluation in one of the scenarios studied in the STRATEGY CCUS Lusitanian case study[4]. This scenario will be evaluated following the approach in Massol et al. (2015) that examines the plants' individual decisions to adopt carbon capture capabilities.[5] Our analysis thus considers 13 distinct industrial clusters labelled E1 to E13 (see Table 3.1-1).[6] Furthermore, the table do provide us an insight on the CO_2 capture cost used in our research.

The cost of building and operating carbon capture equipment varies by industry (Leeson et al.2017). In the present analysis, we consider the CO_2 capture costs presented in Table 3.1-1 that are specific to each cluster and in the range of €50/tCO_2 to €120/tCO_2.[7]

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[3] *The data set also includes a characterization of the level of uncertainty of the country's geological endowment in storage sites.*

[4] *Please refer to D5.2 Report of regional business cases, especially the Portuguese Region.*

[5] *It would require an evaluation of the cost of installing an optimal CCS infrastructure for each of $2^{13} \approx 8192$ coalitions that can be formed by these 13 emitters, which is computationally acceptable.*

[6] *The correspondence between our clusters and the ones used in the STRATEGY CCUS project is detailed in Appendix A.*

[7] *This data set was presented and agreed during the online working meeting that was held on December 2, 2021. These values were representative of the data gathered and produced in the project at that date. Since that date, further refinements may have affected some of these values as part of the developments conducted in the project. Yet, these updates do not substantially affect the present analysis which is predominantly aimed at explaining how cooperative game theoretic notions can be applied to identify the conditions for the emergence of a club of emitters sharing a common transportation infrastructure.*

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	E#01	**E#02**	**E#03**	**E#04**	**E#05**	**E#06**	**E#07**	**E#08**	**E#09**	**E#10**	**E#11**	**E#12**	**E#13**
Facility name	Centro de Produção de Souselas	Fábrica da Marinha Grande	Fábrica SECIL - Outão	Centro de Produção de Alhandra	Santos Barosa - Vidros, S.A	Industria Mineral - Prod Cales não Hidraulicas	GALLOVIDRO, S.A.	Verallia Portugal, S.A.	Fábrica Maceira-Liz	Fábrica Cibra-Pataias	Empresa Produtora de Papel S.A.	Celbi	Soporcel (Navigator Paper Figueira)
Industry sector	Cement	Glass	Cement	Cement	Glass	Cement	Glass	Glass	Cement	Cement	Paper and pulp	Paper and pulp	Paper and pulp
Latitude	40.29	39.74	38.50	38.92	39.74	39.45	39.75	40.14	39.69	39.66	38.49	40.05	40.06
Longitude	-8.42	-8.93	-8.93	-9.01	-8.92	-8.85	-8.93	-8.82	-8.90	-8.99	-8.81	-8.87	-8.85
Captured emission (Mt/y)	0.72	0.19	0.99	1.13	0.29	0.52	0.17	0.19	0.42	0.32	1.79	1.42	0.60
CO2 capture cost (€/t)	61.93	155.03	52.74	51.93	130.63	61.91	227.82	219.56	114.35	125.78	206.09	203.10	214.49

Table 3.1-1: The emission clusters

The map in Figure 3.1-1 illustrates their locations. It should be noted that, with the exception of the Coimbra area, these clusters are predominantly located in the coastal regions and their hinterlands, which is consistent with the spatial distributions of the country's population and heavy industries.

Figure 3.1-1: The geography of the emission clusters and the candidate pipelines and storage sites

We consider the construction of a CCS infrastructure that is aimed at being operated during a 20-year planning horizon starting in 2030.[8] This starting date is consistent with the EU's 2030 Framework for Climate and Energy Policies which takes drastic measures to ensure that CCS can be deployed in the 2030 timeframe through increased R&D efforts and commercial demonstrations over the next decade.

We investigate the possible future deployment of a CCS infrastructure in Portugal. Our analysis considers a total of 13 emission nodes and examines the volumes of CO_2 that can be captured by the glass industries, the cement factories, a lime factory (E#06) and the pulp and paper plants at these emission nodes.

Our assumptions regarding the annual quantities of CO_2 that can be captured under this scenario are based on the simulation results of a model developed in task 5.1 and 5.2 (Coussy, 2021). These simulation results provide for each emission cluster the annual quantity of CO_2 that will be emitted by the pulp and paper, cement, glass plants and lime industry respectively. Only a fraction of these emissions can be captured via CCS.

For simplicity in the current approach we presume that the emission statistics would remain stable over time. Figure 3.1-2 depicts the annual quantities Q_{ij} of CO_2 captured by plants in each industrial sector j at each site i where the color grey is chosen for cement plants and orange, green respectively for glass manufacturing sites, the pulp and paper industries.

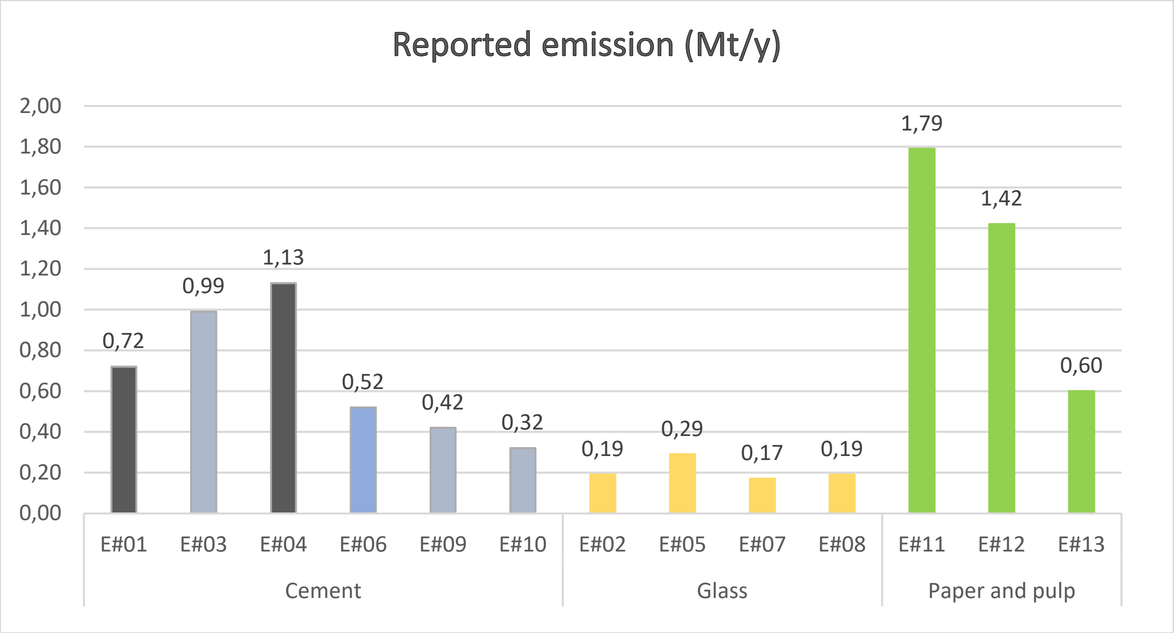

Figure 3.1-2: The capture potentials Q_{ij} at each cluster (in MtCO2/year)

Under this scenario, the total annual quantity that can be captured at these 13 clusters attains 8.75 $MtCO_2$/year.[9] The cement manufacturing sector represents more than a half of the total capture potential (4.10 $MtCO_2$/year). From a spatial perspective, one can remark that the distribution of the clusters' capture potentials is not uniform. An average cluster would have a capture potential of 0.67 $MtCO_2$/year but the two largest clusters (namely E#11 –

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[8] *Note: this starting date is indicative. Delaying it to the second half of 2030 decade has zero impact on the validity of the analysis presented in this document that concentrates on the theoretical conditions for a mutually agreed cooperation using game-theoretic concepts.*

[9] *Notice that not all the CO_2 captured will be stored. By 2050, it is envisioned that about a third of the cumulative captured CO_2 will go for utilisation according to the green hydrogen strategy (see the analysis conducted in D5.2 Coussy et al. 2021)*

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the pulp and paper plant in Setúbal – and E#12 along the coastal area of Figueira da Foz) together account for 36.7% of the overall capture potential whereas the two smallest clusters (namely E#07 at Marinha Grande and E#08 at Figueira da Foz) only capture 4.1% of that total.[10]

3.2 Storage sites

Portugal has a favourable geologic endowment in onshore and offshore underground geologic structures that could supports CO_2 storage. Building on the analyses conducted in other tasks of the STRATEGY CCUS, the present study considers the two cost-effective candidate storage sites presented in Figure 3.1-1 and listed in Table 3.2-1.[11]

Storage Locations	Storage name	Storage volume ($MtCO_2$)	Maximum injection rate ($MtCO_2/y$)	Levelized storage costs[12] (investment and O&M) (€/tCO_2)
S1	S.Mamede Onshore	137	9.15	4.80
S2	Torres Vedras Offshore	239	9.15	14.06

Table 3.2-1: The maximum injection rates and costs of the candidate storage sites

The figures in that table reveal that there are important variations in the capacities and the costs of the storage sites. Because of that variability, a simple pairing of the CO_2 sources with the closest storage site may be neither feasible nor economically efficient. Therefore, it is very important to jointly account for transportation and storage costs when designing the infrastructure.[13] [14]

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10 One could thus wonder whether the two smallest clusters, E7 and E8, should be connected to a CCS infrastructure. In this paper, we have decided to keep them in our list because of their convenient location: both are located along the natural transportation corridors that exist in the central part of Portugal, which suggests that the incremental cost of getting them connected to a pipeline infrastructure should remain reasonable (see Figure 3.1-1).

[11] *It is important to keep in mind that this storage capacity assessment is a low maturity, at Tier 1 for offshore storage, tier 2 for onshore storage.*

[12] *Note: the values of the storage costs are indicative and will be further researched in the project. Because of the specific structure of the problem at hand, any revision will not substantially modify the results (e.g., in case of a storage costs of 6.80 €/tCO_2 for S#1, an extra 2 €/tCO_2 will be added on the break-even price for joint CCS adoption in the Southern region reported in section 6.*

[13] *Indeed, simply pairing the sources with the closest sinks ignores the technical constraints that may hamper the feasibility of such a simplistic solution and does not necessarily minimize the total system cost.*

[14] *From a technical perspective, the STRATEGY CCUS team has decided to curb down the uncertainty regarding the site maturity, required depths and the expected reservoir injectivity by implementing a limit of 1 $MtCO_2/y$ per well as the maximum annual injection rate per well, regardless of the modelling tool (with the existing permeability data) indicating that the injection rates in each well could be higher. Due to the fact that our optimization model does not take the number of injection wells in consideration as a factor, the maximum injection rate is fixed at 9.15 $MtCO_2/y$ for both of the storage sites.*

3.3 Pipelines

A dedicated pipeline infrastructure is the only economically viable transportation solution that can carry the large quantities emitted by large stationary sources of CO_2. In the present analysis, a predefined list of 22 candidate pipelines was considered (cf. Appendix A) that could be installed to connect the emission clusters nodes E#01 to E#13 with the candidate storage nodes S#01 to S#02. From that list of candidate pipelines, we consider a realistic network that accounts for Portugal's mountainous geography (terrain, water bodies, landforms, natural transportation corridors). The pipelines and the pipeline network were designed using the transport module in D5.1 (Coussy, 2021) and was conducted by the Portuguese team in the scope of the Lusitanian basin scenario development for D5.2. (Coussy, 2021). As shown in the Figure 4.1-1, these pipelines are located along the country's main transportation corridors. From a cost perspective, we assume that the total cost to transport a given flow of CO_2 on a point- to-point pipeline system is directly proportional to the length of that pipeline and that the total cost per unit of distance can be decomposed into a fixed investment cost component, a variable investment cost one that is linearly varying with the transported flow of CO_2 and a unit O&M cost. Regarding the pipeline investment cost components, our approach follows the costing methodology used in Morbee et al. (2012) and is detailed in Appendix A. For concision, we simply highlight here that for a 100km long onshore pipeline aimed at being installed on a flat terrain, we assume an annual equivalent fixed cost of €4.6 million and an annual equivalent variable cost of €0.16 per (tCO_2×100 km). In case of a mountainous geography, a correction is applied to these figures to account for the specific nature of terrain observed along each pipeline route. The obtained cost figures are thus specific to each pipeline route. Regarding O&M cost, IEA (2005) indicates that the annual operation costs vary between €1.0 and €2.5 per (tCO_2×100 km). In our analysis, we use a value of €1.5 per (tCO_2×100 km).

4 Optimal CCS infrastructure deployment in Portugal

In this section, we look at the most cost-effective design of CCS infrastructure for storing the CO_2 gathered in the planned scenario. Then we look into whether the Portuguese infrastructure needs to be analysed as a single integrated national infrastructure or if it may be broken down into regional subsystems.

4.1 Infrastructure deployment at the lowest possible cost

We implement an optimization problem aimed at determining the most cost-effective architecture of a CCS infrastructure capable of transporting and storing CO_2 gathered at the Portuguese clusters. Appendix B has a formal description of this mathematical programming problem. The goal is to select pipelines and storage sites (from a predetermined and finite list of candidate pipelines and storage sites) that have the lowest total annual equivalent cost of construction and operation of pipeline and storage infrastructure. We consider the year 2050 as a reference year for this simulation. Our assumption imposes the overall national demand for CO_2 capture and thus the annual storage required in that year.

However, emitting clusters and storage sites need to be connected in a cost-effective manner. The model therefore seeks to minimize the total infrastructure cost by identifying the following optimal decisions: (i) whether, among a finite list of possible pipeline routes (linking either an emission cluster to a storage site, an emission cluster to a transit node, two emission nodes, two transit nodes, or a transit node to a storage site), a given corridor should be open, given its incurred fixed cost of deployment, and the transported quantity on that corridor given the variable operation cost; and (ii) the annual (possibly null) volume of CO_2 injected in each storage site, given an exogenous, site-dependent unit cost of storage operations.

As an outcome, we obtain a 2050-based static picture of the optimal – in least-cost sense – CO_2 pipeline network that matches the demand for storage with the existing capacities and possible routes. We have run this model on

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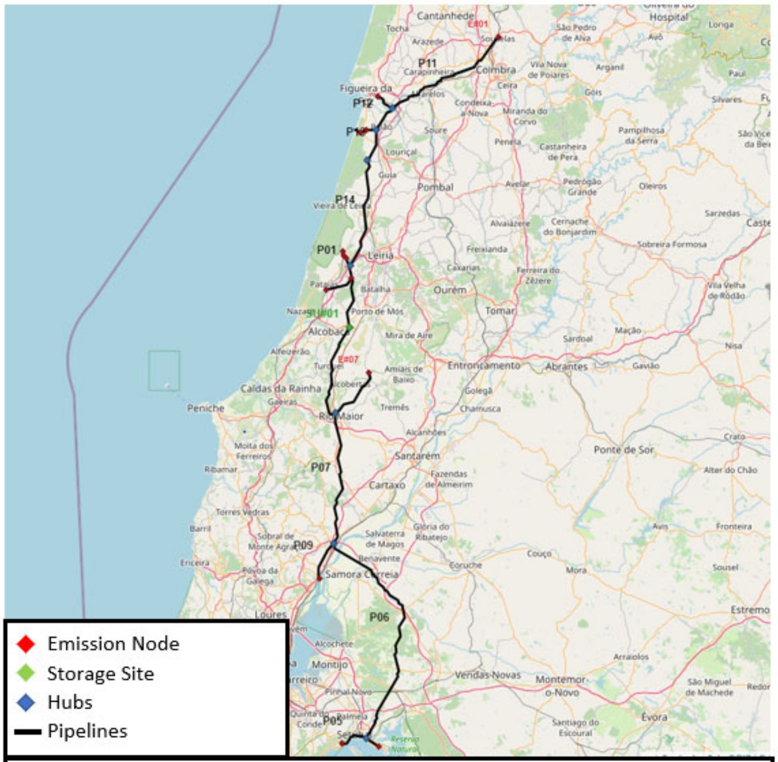
the above-mentioned input data to identify the ideal CCS infrastructure supporting our capture scenario. The results are illustrated in Figure 4.1-1.[15]



Total volume of CO_2 captured and stored:	8.75 $MtCO_2$/y
Total length of the pipeline system:	309.39km
Total equivalent cost :	€73.68 million
- *Total equivalent pipeline cost:*	*€31.68 million (43% of the total)*
- *Total equivalent storage cost:*	*€42.00 million (57% of the total)*

Figure 4.1-1: CO_2 pipeline and storage deployment in Portugal

At first sight, one could conjecture from the map that the offshore storage site was not taken into consideration as a potential storage site. Due to the extremely high levelized storage costs of the offshore storage, the onshore storage site posits itself as a better alternative since it has the capacity to store the total annual CO_2 emissions of the 13 industrial sites at a lower cost.[16] Therefore, in the presence of a sole storage site, the optimization model does recommend the construction of a fully connected national pipeline system. From the reasoning above, one could conjecture that there is no necessity to do a subadditivity test. It's important to remember that the

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[15] *It is important to stress that the present study omit the possible utilization of a portion of the CO_2 captured as part of the green hydrogen strategy. Yet, the analysis is Deliverable 5.2 (see Coussy et al., 2021b) indicates that, by 2050, that portion could represent about a third of the cumulative captured volume.*

[16] *Note: the work conducted in D5.3 shows that the costs are higher than the onshore, obviously, but the difference is not extremely high. In the same vein, it is important to keep in mind that the cost data used in the present analysis is solely based on techno-economic evaluations. Hence, an enlarged perspective accounting for social acceptance issues (and the associated costs) could make the offshore option more adequate. Yet, valuing the cost implications of these social acceptance issues is beyond the scope of the present paper which is why we concentrate on available techno-economic cost evaluations.*

morphology of these pipeline connections is highly situation dependent, and it could change dramatically if additional potential storage locations are present, as well as the need for subadditivity tests.

4.2 Notion of separability

Even though the need for a subadditivity test is futile due to the previously mentioned reasons, the notion that the system can be separated is something to be pondered upon. The possibility of separating the system into subsystems might provide the flexibility to implement the deployment of a CCS infrastructure since the project can be carried out even if certain parties opt out to exercise their stand-alone position. For example, if the fully connected national pipeline system is simply divided into two subsystems based on the basic cardinal direction (e.g.: North and South), the southern subsystem can still be built without the consensus of the northern emitters and vice versa. Therefore, in order to investigate the separability of the system, let us consider two coalitions based on the same cardinal directions. To study an emissions-transit-storage nodes subsystem, let's call it S, separately from the rest of the national system, we need to make sure it doesn't interface with any other subsystem.

Therefore, all the emission clusters that are located in the upper part of the onshore storage site will be aggregated and considered as the northern coalition. Hence, S^{North} refers to the northern coalition: S^{North} = *{E#1, E#2, E#5, E#7, E#8, E#9, E#10, E#12, E#13}*. Contrarily, the rest of the emission clusters are naturally found in the southern coalition, denoted by S^{South} = *{E#3, E#4, E#6, E#11}*. Each of these coalitions represents a candidate subsystem of emission areas that could potentially be separated.

In formal terms, we let N denote the set of all the emission clusters considered in a given scenario and Q_i denote the total annual quantity of CO_2 captured in cluster i. For each coalition S, we evaluate two types of costs. First, by setting $Q_i = 0$ for the emission clusters i in the grand coalition N but not in S (i.e., for all $i \in N/S$), we can solve the mathematical programming problem in Appendix B to evaluate $C(S)$ the stand-alone cost of serving S. This is the total cost of installing a pipeline and storage infrastructure optimally designed to serve the needs of the emission clusters in S. Second, we also use that optimization problem to assess the extra cost that this coalition S imposes on a coalition S' that gathers emission clusters in the remaining subset (i.e., $S' \in N/S$). This is the incremental costs $C(S \cup S') - C(S')$ imposed by S on S'. Accounting for all the possible non-empty coalitions S' that can be formed by the emission clusters in N/S and letting N/S denote the number of elements in N/S, a total of $2^{|N/S|} - 1$ incremental costs have to be evaluated for each coalition S . If for a given coalition S and any coalition S' in N/S, the stand-alone cost $C(S)$ equals the incremental cost $C(S \cup S') - C(S')$, the cost function is said to be separable because it verifies $C(S \cup S') = C(S') + C(S)$. So, if these $2^{|N/S|} - 1$ equality conditions hold, there are no cost interactions between the emission clusters in S and the others in N/S and one can separately examine the deployment of a CCS infrastructure aimed at solely serving S without paying attention to the other emission clusters.

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Coalition S	Stand-alone cost (M€)
S^{North} = {E1, E2, E5, E7, E8, E9, E10, E12, E13}	32.79
S^{South} = {E3, E4, E6, E11}	40.89
Combined total of the both northern and south coalition	**73.68**
Total cost of the grand coalition N	**73.68**

Table 4.2-1: The stand-alone cost for each respective coalition.

These cost comparisons show that the concept of separability is quite present in the fully integrated national infrastructure, as seen in Table 4.2-1. The northern and southern systems do verify the conditions for a separable cost function. As a result, it is possible to build two distinct subsystems that share the same storage location S1. In the next section, we divide the Portuguese emission clusters into these two subgroups and investigate the prerequisites for the deployment of two autonomous CCS infrastructures, dubbed North and South, respectively. Figure 4.2-1 shows a diagram of the breakdown.

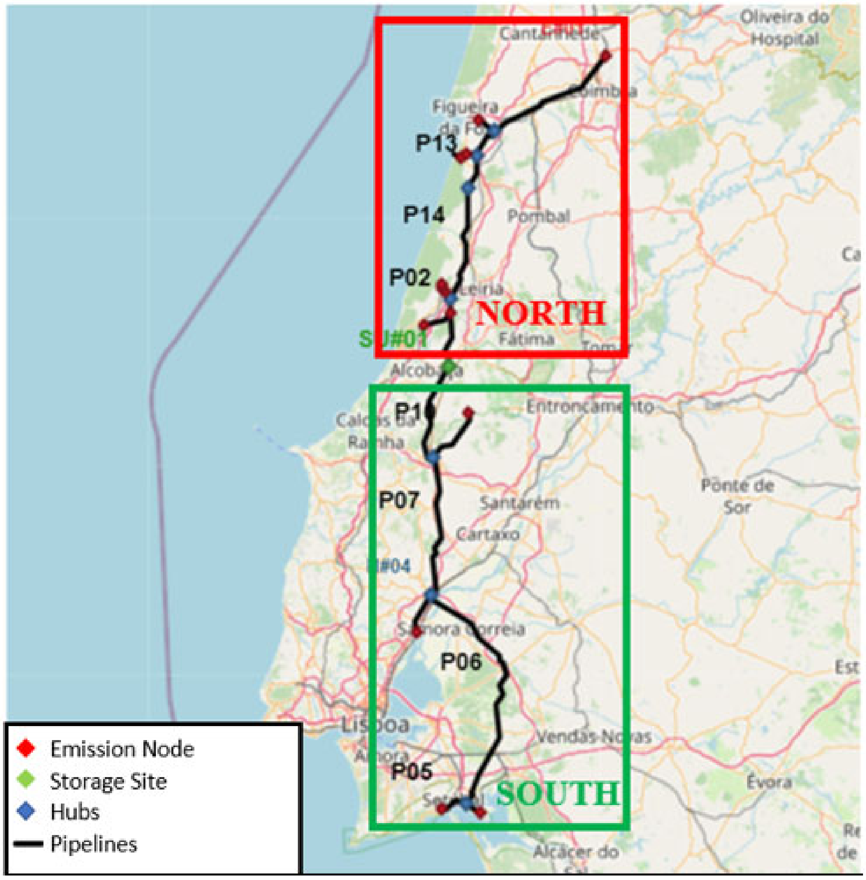

Figure 4.2-1: An illustration of the two independent subsystems

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5 Methodology: A cooperative game theoretic architecture

We begin by giving a non-technical overview of our cooperative game-theoretic framework in this section. The conditions that must be confirmed before the building of a shared infrastructure can be decided are then detailed in two subsections. Finally, we establish the break-even CO_2 price for joint CCS adoption and demonstrate how to evaluate it.

5.1 Cooperative game and stability concept

We consider a fully connected national pipeline system of emission clusters, similar to the one described in the previous section, and investigate the conditions for constructing the least-cost CCS infrastructure in that system, as well as the conditions for constructing the least-cost CCS infrastructure in the preceding section. Hereafter, as mentioned previously, N refers to the grand coalition joining all the emission clusters in that subsystem: *N= {E#1, E#2, E#5, E#7, E#8, E#9, E#10, E#12, E#13}* in the northern region or *N={E#3, E#4, E#6, E#11}* in the southern region.

A CO_2 pipeline and storage system is, by definition, a mutualized infrastructure, and its cost must be shared by all those who feed CO_2 into it. In this study, we assume that each emission cluster is an autonomous decision-making entity (however, we should note that we could have different plants of the same company in different clusters) that can either feed all the CO_2 acquired by local emitters to the grand infrastructure, feed them to a different infrastructure, or renounce CO_2 capture. For the time being, we will simply treat all the emitters in a given emission cluster as a monolithic agent, that is, as a single player.

According to *Young (1985)*, the players are expected to negotiate with one another to obtain a binding agreement over the distribution of the overall cost of developing and operating the grand infrastructure. To look at the numerous choices for player collaboration inside a game, we must first figure out how much each subgroup of players S in the set N may spend collectively. Indeed, if a subset of players believes that it is paying more than it might achieve on its own, it may elect to forego conversations with other players and adopt a stand-alone approach (i.e., develop its own infrastructure). Here, a total of $2^{|N|} - 2$ coalitions S with $S \subset N$ and $S \neq \emptyset$ and $S \neq N$ can be formed. As a result, our objective is to see if the entire cost of the grand infrastructure can be apportioned in such a way that none of these subsets of participants is forced to dissolve. Such a cost allocation is said to constitute the "core" of the cost game.

5.2 The core of the cooperative cost game

We now assume that the pipeline and storage infrastructure aimed at serving the needs of the grand coalition N is supplied by a unique operator. The total cost incurred by that operator is $C(N)$. We let $r = (r_1, \dots, r_{|N|})$ where r_i is the amount charged to the emission cluster i, denote the revenue vector charged by that operator. We assume that this operator is compelled to charge a revenue vector that allows him to recover its cost and thus:

$$\sum_{i \in N} r_i = C(N) \qquad \textbf{(1)}$$

Each coalition of emission clusters S compares: $\sum_{i \in N} r_i$, the amounts charged by the operator with $C(S)$ the cost it would incur by deviating and adopting a stand-alone attitude. The condition for all coalitions to rationally remain in the grand coalition is:

$$\sum_{i \in N} r_i < C(S) \, , \quad \forall \, S \subset N, S \notin \{\emptyset, N\} \qquad \textbf{(2)}$$

The set of revenue vectors that verifies conditions (1) and (2) is named the core of the cooperative cost game (N, C). From an empirical perspective, it is possible to verify that the core is not empty by using a linear programming

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approach similar to the one presented in Massol et al. (2015, Appendix B). The non-emptiness of the core indicates that it is possible for the infrastructure operator to charge a revenue vector that allows him to recover its cost while preventing the secession of the players.

5.3 The individual conditions required for CCS adoption

We now examine the emission clusters' decision to adopt the proposed CCS project. We let χ_i denote the unit cost of the carbon capture operations conducted at cluster *i*. The definition of that unit capture cost will be further discussed in a subsequent section. For any emission cluster *i*, the amount $(p_{CO_2} - \chi_i)Q_i$ represents its willingness to pay for a CO_2 pipeline and storage service and, thus, the amount $(p_{CO_2} - \chi_i)Q_i - r_i$ is its individual net benefit. Because of individual rationality, the infrastructure operator must provide a non-negative net benefit to each individual emission cluster, i.e.:

$$(p_{CO_2} - \chi_i)Q_i - r_i \geq 0 \qquad \forall\, i \in\, N. \tag{3}$$

5.4 The break-even price for joint CCS adoption

According to Massol et al. (2015), setting a revenue vector that validates requirements (1), (2), and (3) is a condition for the pipeline operator to be able to create the grand infrastructure. The prevailing carbon price has a direct impact on the net benefit of emission clusters, and hence on the infrastructure operator's ability to select an incentive-compatible revenue vector. As a result, we define $p^*_{CO_2}$, the break-even price for joint CCS adoption, as the crucial value in the CO_2 emissions charge that is compatible with satisfying the three requirements. The solution to the following linear program LP1 yields this break-even price:

LP1:

$$\underset{r, p_{CO_2}}{\text{Min}}\; p_{CO_2} \tag{4}$$

s.t.

$$\textstyle\sum_{i\,\in N} r_i = \; C(N) \tag{5}$$

$$\textstyle\sum_{i\,\in N} r_i < \; C(S)\,, \quad \forall\, S \subset N, S \notin \{\emptyset, N\} \tag{6}$$

$$(p_{CO_2} - \chi_i)Q_i - r_i \geq 0 \qquad \forall\, i \in\, N. \tag{7}$$

6 Results and discussion

We now use the site-specific capture costs together with the transportation and storage costs evaluated with the optimization model in Appendix B to evaluate the break-even price for joint CCS adoption. Before we start determining the break-even price, several scenarios were created in order to obtain a better understanding of the current case.

As can be observed in the Table 3.1-1, some of the CO_2 capture technologies deployed among the 13 emitters constituting the largest coalition indicated N_{all}, do cost way more than their counterparts. Therefore, we have decided to implement some measures towards a "partial coverage" scheme whereby emitters that have attained and surpassed a threshold CO_2 capture cost of €150/tCO_2 are discarded from the study. In the case of a "partial coverage" scheme, six emitters with the highest CO_2 capture costs (E#2, E#7, E#8, E#11, E#12, and E#13)[17] are eliminated from the list of potential CCS adopters and denote N_{small} , the coalition of emitters with CO_2 capture cost lower than the threshold. This coalition of emitters will also be divided into two sub-coalitions based on the previously mentioned cardinal direction due to the presence of separability in the system, as they will be denoted as N_{small}^{north} for the northern region and as N_{small}^{south} for the southern region. In this case study, we are going to systematically contrast the results obtained with six possible extents of coverage, i.e., the six possible definitions of the grand coalition N, N_{all}, N_{all}^{north}, N_{all}^{south}, N_{small}, N_{small}^{north} and N_{small}^{south}.

Using the foregoing list of possible emitter groups (i.e., grand coalition N definitions), we compute the minimal CO_2 price necessary to secure voluntary adoption of CCS technology by all members for each of these coalitions. Table 5.4-1 summarizes these findings.

Grand Coalition $\boldsymbol{N}$	Average infrastructure cost of the entire CCS chain €/ (tCO_2 per year)	Voluntary adoption of CCS by all members $\boldsymbol{P_{CO_2}}$ €/ (tCO_2 per year)
N_{all}	146.68	233.64
N_{all}^{north}	169.11	233.64
N_{all}^{south}	124.80	213.49
N_{small}	81.65	136.39
N_{small}^{north}	107.26	136.35
N_{small}^{south}	64.67	69.31

Table 5.4-1: The minimum prices of CO_2 required to organize a group of certain size

First and foremost, we discuss the absolute magnitude of these costs. These absolute limits, while very high in comparison to current carbon pricing, do not appear to be insurmountable in the medium term. Nonetheless, the

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[17] *It is important to stress that, in the present analysis, we do not consider the possibility for some of these emitters (e.g., the paper and pulp sector which is biomass-fuelled) to develop a stream of revenues from selling CO_2 for utilisation.*

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CO_2 price discovered in our study is more or less comparable to the global average CO_2 capture cost projected by the IEA's landmark Net Zero Emissions by 2050 Scenario (NZE), which lays out a narrow but achievable path to 1.5°C global temperature stabilization and other energy-related sustainable development goals. For example, carbon prices are in place in all regions and will rise by 2050 to an average of \$250/tCO_2 (€222.7 /tCO_2) in advanced economies, to \$200/tCO_2 (€177.7/tCO_2) in other major economies (in China, Brazil, Russia, and South Africa), and to lower levels elsewhere.

Second, as can be expected, we can see that the required price for the deployment of a CCS infrastructure can be large, especially in the north that gathers several emission clusters with high CO_2 capture cost. This is particularly true for the scenarios in which all plants are included ("All"), regardless of their cardinal direction.[18]

As a side remark, let's have closely examined the solutions of the linear program LP1 for the specific scenario which represents the whole grand coalition N,N_{all}.By construction, the solution of LP1 is such that at least one of the constraints (7) – recall that they state that the individual net benefit of each emission cluster must be non-negative – must be binding. Interestingly, there are two unique binding constraints: the ones associated with the emission clusters E7 and E8. The common point among these clusters is that their CO_2 capture costs are exceptionally expensive relative to their low annual emissions. A closer examination of LP1 reveals that these cluster emissions do have the largest incremental cost that they impose on their counterparts. Hence, the pipeline operator charges them the lowest without creating an opportunity for other emitters to disband. The need to include these two emission clusters into the system is up for further discussion especially when the prevailing CO_2 price is exceedingly high. Hence, the scenario "Small" might prevail as an alternative solution for this Portuguese case as 44% reduction in average infrastructure cost and 42% reduction in CO_2 price can be observed.

Thirdly, the criterion (7) for all club members to voluntarily adopt CCS technology demands a carbon price level that is much higher than the average total cost of the CCS chain in all of these groupings. Even the 'partial coverage' scheme where the emission clusters with CO_2 capture cost larger than €150/tCO_2 are eliminated, the carbon prices still remain noticeably high. This conclusion has significant policy implications for CCS technology implementation, questioning the validity of the simple accounting based on cost-engineering-based studies that evaluate the average total cost of a CCS supply chain (by simply dividing the total infrastructure cost by the total quantity stored). As mentioned in Massol et al. (2015), it implicitly presumes that this figure can be interpreted as the critical price of CO_2 required to trigger the construction of CCS infrastructure.

Our finding indicates that this engineering approach can significantly underestimate the price at which CCS will be adopted by the grand coalition at stake. For example, below a CO_2 price of €233.64/tCO_2, there is no way to obtain the adhesion of all emitters in N_{all} to the infrastructure project. The difference between the price level and the average total cost of the whole CCS chain is larger than €86.96/tCO_2 and clearly matters as it represents 159% average total cost of the CO_2 pipeline system. As can be observed, this phenomenon remerges in all the prelisted grand coalition studied in this analysis. The difference between the break-even prices for these infrastructures is significant, and the figures derived from simple accounting reasoning notably underestimate the true break-even price capable of enabling all emission clusters connected to the infrastructure to adopt CCS technology cooperatively. This indicates that ignoring strategic motivations might result in a considerable underestimating of the challenges of implementing a CCS infrastructure that connects several emission sources.

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[18] *That said, some of these emission clusters are fuelled by biomass and the corresponding volumes of captured CO_2 may provide revenues from utilisation that are not considered in the present analysis.*

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7 Conclusion and policy implications

The question of how to organize the construction of a large-scale CO_2 pipeline and storage system is one of the key issues that policymakers must address to support the large-scale deployment of Carbon Capture and Storage (CCS) technologies. The main objective of the task 5.4 is to investigate and comprehend the need of using game theory to account for the coordination of players along the chain in order to maintain a viable and mutually agreed-upon collaboration. This report thus adopts a spatial approach to elucidate the requirements that enable the creation of a shared pipeline and storage infrastructure with network characteristics a sensible decision for a group of regional clusters of industrial emitters that may be connected to such infrastructure.

Taking Portugal as a case study, the report examines the least costly deployment of a national CCS infrastructure. A closer examination of their cost structures (i.e., the separability of the cost function) reveals an important finding: this national infrastructure can be decomposed into two regionally distinct subsystems in the north and south of Portugal, implying that no pipeline connects any of these regions in any of the scenarios under consideration. Since these subsystems may be deployed individually, there is no need for policymakers to focus their emphasis on the creation of a large-scale national infrastructure; instead, a regional strategy to CCS deployment should be preferred.

The report then examines the economic feasibility of these regional subsystems. Using an adapted cooperative game-theoretic framework, we model the outcomes of the negotiations among the emission clusters that can be connected to these infrastructures and use it to determine the critical values in the charge for CO_2 emissions that makes their constructions possible: the break-even prices for CCS adoption. From the standpoint of policymakers, a comparison of these break-even prices yields a number of intriguing results.

This analysis calls for further attention to be paid to the CO_2 capture costs of the CCS supply chain when trying to infer the break-even price of these infrastructures. Indeed, the high capture costs of certain emitters have a direct impact on determining the price for CCS infrastructure adoption. Moreover, the incremental cost of these emitters is also highly impacted as well, where the amount that can be charged by the infrastructure operator without inciting a disband among the participants is something to bear in mind. Consequently, these emission clusters with large CO_2 costs relative to their low annual CO_2 emissions are the least attractive candidates to be included in the potential coalition for CCUS adoption. Therefore, it is important to revisit the Portuguese scenario and to further discuss and analyse the necessity of adding emissions clusters of this nature into the system, as they might be the catalyst that hinders the process of CCUS adoption in that particular region.

As in any model-based analysis, the discussion in this paper is based on a simplified representation that can be extended in several directions. First cost-engineering analyses based on average cost approaches may understate the exact break-even price needed for the joint decision to build these infrastructures. For example, we overlooked the impact of uncertainty. Because carbon capture expenditures are irreversible, uncertainty might impact emitters' individual decisions and, as a result, the viability of a shared infrastructure. As a result, risk-averse shareholders may demand a greater premium to compensate for the investment's risk. Further study might be done to see if individual decisions made using a real-options framework can be integrated with cooperative decision-making. Second, further improvement may be achieved by converting the static framework analysis into a dynamic one that includes the time horizon in order to reproduce the precise scenario created by the STRATEGY CCUS team. However, incorporating the system implications of individual selections into a real-option framework or converting a static analysis into a dynamic framework might be daunting. Third, utilisation and its impacts are another element that could attract further research. In the present analysis, the design of the pipeline infrastructure is led by the location of both CO_2 sources and storage sites whilst in CCU, one also has to consider the location of the industrial clusters that use the captured CO_2 as a feedstock for the manufacturing of other products. As a substantial share of the cumulative volume of CO_2 to be captured until 2050 will be directed to utilisation, it can be opportune to enrich the present modelling framework to inform policy & decision making regarding the green hydrogen strategy. Four, the CO_2 for methanation will come from sources using bioenergy (essentially pulp and paper and partially from cement). For these sectors, CO_2 capture is not required to reach net-zero and further research will be useful to evaluate the revenues that can be derived from CO_2 utilisation and how these revenues affect their willingness to join a common network.

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9 Appendix A: Emission cluster and potential pipelines

9.1 The emission clusters

We build upon the results gained from the WP2: Mapping Technical Ascpects (see Mesquita and Carneiro, 2020) and WP5: Planning CCUS scnarios (see Coussy, 2021a,b) activities of the EU-funded STRATEGY CCUS project to group emitters into clusters of reasonable size. From a database including the technical characteristics and geographical location of the Portuguese stationary sources, the STRATEGY CCUS team conducted an exhaustive clustering exercise that resulted in the identification of 68 sources of CO_2 in Portugal that aggregate the emissions of the neighboring industries and power plants. Only 20 of the region's 68 industrial emission sites are considered suitable CO_2 capture targets, with fossil CO_2 emissions ranging from 0.08 $MtCO_2$/y to 2.79 $MtCO_2$/y. In 2018, those twenty sources emitted a total of 12.66 Mt/y, accounting for 97% of overall emissions in the region and 42% of national stationary CO_2 emissions. They then simulated the future emission trajectories of each of these industrial sectors, using a detailed analysis of their predefined scenario. From their simulation results, it appears that 13 sources account for the largest share of the nation’s industrial emissions of CO_2 and offer the most promising prospects for the installation of carbon capture capabilities. Then, these 13 sources are labeled E#1 to E#13. The following Table 9.1-1 clarifies the construction of our industrial clusters from the sources of CO_2 considered in the one of the predefined scenarios for Portuguese region in STRATEGY CCUS project.

Scenario unit ID	Facility name	Industry sector	Emitter ID
E#01	Centro de Produção de Souselas	Cement	PT.ES.003
E#02	Fábrica da Marinha Grande	Glass	PT.ES.016
E#03	Fábrica SECIL - Outão	Cement	PT.ES.005
E#04	Centro de Produção de Alhandra	Cement	PT.ES.002
E#05	Santos Barosa - Vidros, S.A	Glass	PT.ES.014
E#06	Industria Mineral - Prod Cales não Hidraulicas	Lime	PT.ES.008
E#07	GALLOVIDRO, S.A.	Glass	PT.ES.018
E#08	Verallia Portugal, S.A.	Glass	PT.ES.017
E#09	Fábrica Maceira-Liz	Cement	PT.ES.009
E#10	Fábrica Cibra-Pataias	Cement	PT.ES.011
E#11	Empresa Produtora de Papel S.A.	Paper and pulp	PT.ES.010
E#12	Celbi	Paper and pulp	PT.ES.019
E#13	Soporcel (Navigator Paper Figueira)	Paper and pulp	PT.ES.012

Table 9.1-1:The correspondence between our industrial clusters and the sources of CO_2 used in Strategy CCUS

9.2 The candidate pipelines and their costs

9.2.1 Definition

Each pipeline connects two of 23 nodes: the 13 emission clusters nodes E#1 to E#13, the two storage nodes S#1 to S#2 and the 8 intersection nodes labelled R#1 to R#8 that are listed in Table 9.2-1. The later nodes represent possible network intersections between at least three pipelines. There are no CO_2 injection into/withdrawal from the network at these nodes.[19]

Hub	Cluster name	Region
R#1	Rio Maior	Alentejo
R#2	Carregado	Centro
R#3	Setubal	Lisboa
R#4	Copeiro	Centro
R#5	Amieira	Alentejo
R#6	Marinha das Ondas	Centro
R#7	Telheiro	Centro
R#8	Leiria	Centro

Table 9.2-1:The intersection nodes

Table 9.2-2 presents the candidate pipelines, their lengths, and the dimensionless average terrain-correction factors τ that will be needed to evaluate the transportation costs. These data are based on the analysis conducted by the Portuguese team in deliverables D5.1 and D5.2 (see. Coussy et al., 2021a,b).

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[19] *The assumptions retained in the present analysis are largely based on the work conducted by the Portuguese team in deliverables D5.1 and D5.2 (see. Coussy et al., 2021a,b).*

Pipeline	Origin	Destination	Distance (km)	Average terrain cost factor
P#1	E#5	R#7	2.55	1.44
P#2	R#7	E#9	3.71	1.43
P#3	E#9	S#1	15.05	1.28
P#4	E#2	E#5	1.21	1.72
P#5	E#3	R#3	8.66	2.54
P#6	R#3	R#2	70.3	1.24
P#7	R#2	R#1	39.37	1.19
P#8	R#1	S#1	28.62	1.28
P#9	E#4	R#2	11.63	1.32
P#10	E#6	R#1	16.4	1.26
P#11	E#1	R#5	37.97	1.28
P#12	R#5	R#4	7.72	1.18
P#13	R#4	R#8	9.51	1.3
P#14	R#8	R#7	31.91	1.27
P#15	E#7	E#2	1.25	1.8
P#16	E#8	R#5	5.74	1.36
P#17	E#10	E#9	8.37	1.36
P#18	E#11	R#3	4.49	1.53
P#19	E#12	E#13	1.85	1.39
P#20	E#13	R#4	3.06	1.4
P#21	R#6	S#2	1.66	1.37
P#22	E#12	R#6	32.00	3.00

Table 9.2-2 : The candidate pipelines (source: Coussy et al., 2021a,b)

9.2.2 The pipeline investment cost

We follow the standard methodology retained in CO_2 pipeline models and assume that the construction cost of a point-to-point pipeline infrastructure is directly proportional to its length. We thus consider a normalized cost per unit of length and assume that this cost can be evaluated as follows.

To evaluate the total annual equivalent investment cost of a 100km-long pipeline, we use the pipeline investment cost formula detailed in Morbee et al. (2012) to obtain the total capital expenditures and convert them into an annual equivalent cost using a 7% discount rate and assuming an infrastructure lifetime of 30 years. The annual equivalent investment cost of a 100km-long pipeline that has a steady annual output of q $MtCO_2$/year is: $(A_0 + B_0)\tau$, where A_0 = 4.6045 is the fixed cost coefficient (in million euros), the variable cost coefficient is B_0 = 0.1641 in euros per (tCO_2×100 km) and τ is the average terrain correction factor described in WP1 and detailed in Table 9.2-2.

10 Appendix B – Designing an optimal pipeline-storage infrastructure

This Appendix details the optimization problem used to evaluate the least-cost design of a given pipeline-storage infrastructure. We first present the notations before presenting the mathematical formulation of that problem.

10.1 Notation

To begin with, we define three sets to identify the nodes of the network:

- $N = \{1, \dots, i, \dots, |N|\}$ the set gathering the clusters where the captured emissions are injected into the network;
- $S = \{1, \dots, i, \dots, |S|\}$ the set gathering the storage nodes where CO_2 is withdrawn from the network to be injected in an underground storage;
- $R = \{1, \dots, i, \dots, |R|\}$ the set of the network routing nodes that are neither connected to an emission cluster nor to a storage site. These nodes typically represent an intersection between several pipeline links.

The three sets are mutually exclusive so: $N \cap S = \emptyset$, $S \cap R = \emptyset$ and $N \cap R = \emptyset$. For notational convenience, we also let denote $Z = N \cup S \cup R$ the macro-set regrouping all the nodes and z is used as a generic notation for a given node in Z. We also let $P = \{1, \dots, i, \dots, |P|\}$ denote the set of candidate pipeline links.

We now present the exogenous parameters.

- Q_i is the total quantity captured and injected into the network at cluster i ;
- $\overline{Q_s}$ is the maximum amount of CO_2 that can be withdrawn from the network to be injected into storage s;
- $I_{p,z}$ is an incidence parameter that only takes three values: -1 if pipeline p starts at node z, 1 if pipeline p ends at node z, and 0 otherwise;
- F_p^{pipe} is the fixed cost incurred to open the pipeline link p;
- C_p^{pipe} is the unit cost incurred by using pipeline p;
- C_s^{inj} is the unit cost of the CO_2 injection operations conducted at storage s;
- M is an arbitrarily large constant. Its value will be discussed below.

The decision variables are:

- δ_p is a binary variable that describes whether the pipeline link p is opened (i.e., $\delta_p = 1$) or closed (i.e., $\delta_p = 1$);
- q_p^+ (respectively q_p^-) is the non-negative quantity transported using pipeline p that flows in the direction posited for pipeline p (respectively in the opposite direction);
- q_s^{inj} is the non-negative quantity injected into storage *s.*

For notational simplicity, we also let $x_N = \left(\delta_p, q_p^+, q_p^-, q_s^{inj}\right)$ be the decision vector to transport and store the emissions captured at the clusters in N .

10.2 Optimization problem

The cost-minimizing design of an infrastructure gathering the emissions captured at the emissions clusters in *N* and transporting them to the storage site can be determined using the following optimization problem:

$$\text{MILP1}: \quad \underset{x_N}{\text{Min}} \sum_{p \in P} \left[F_p^{pipe} \delta_p + C_p^{pipe} \left(q_p^+ + q_p^-\right)\right] + \sum_{s \in S} C_s^{inj} q_s^{inj} \tag{B.1}$$

$$\text{s.t.} \quad \sum_{p \in P} I_{p,i} \left(q_p^+ - q_p^-\right) + Q_i = 0, \qquad \forall i \in N, \tag{B.2}$$

$$\sum_{p \in P} I_{p,s} \left(q_p^+ - q_p^-\right) = q_s^{inj}, \qquad \forall s \in S, \tag{B.3}$$

$$\sum_{p \in P} I_{p,r} \left(q_p^+ - q_p^-\right) = 0, \qquad \forall r \in R, \tag{B.4}$$

$$q_p^+ + q_p^- \leq \delta_p M, \qquad \forall p \in P, \tag{B.5}$$

$$q_s^{inj} \leq \overline{Q_s}, \qquad \forall s \in S, \tag{B.6}$$

$$q_s^{inj} \geq 0, \qquad \forall s \in S \textit{ and } \delta_p \in \{0,1\}, q_p^+ \geq 0, q_p^- \geq 0, \forall p \in P. \tag{B.7}$$

In this mixed-integer linear programming problem, the objective function (B.1) to be minimized is the sum of the total pipeline cost and the storage annual equivalent cost. The constraints (B.2), (B.3) and (B.4) respectively represent the mass balance equations at the source, storage, and intersection nodes.

For each pipeline p , the constraint (B.5) forces the binary variable δ_{p} to be equal to 1 whenever a positive quantity of gas is flowing into that pipeline (whatever the flow direction) and imposes a zero flow whenever it is optimal not to build it.[20] The constraints (B.6) represent the sink injectivity constraints: at each storage node, the quantity injected cannot exceed the local injection capacity.

We let x_N^* be the solution to that problem. Observe that this solution is such that on each pipeline p , at least one of the two directed flows $q_p^{+^*}$and $q_p^{-^*}$ must be equal to zero.[21] One can note that this specification accounts for the storage injection constraints but ignores the fact that storage operations could also be limited by the cumulated volume that can be injected at a storage site. This simplification has been adopted because of the relative magnitudes of the volume and injection capacities of the storage sites listed in Table 2.

Remarking that on each storage site, an annual injection flow set at the injection capacity for 30 years (i.e., the duration of our planning horizon) systematically yields a cumulated volume CO_2 that is strictly lower than the site's total volume, we have decided to omit that constraint to limit the size of the optimization problem and thus the overall computational time (recall that this model must be solved for every possible coalition of emission clusters that can be formed).

Overall, this mixed-integer linear programming problem is similar to the pipeline routing problem examined in Morbee et al. (2012) but, in contrast to their model, ours uses a simpler static time representation (i.e., a single representative year) but conveys a richer representation of the transport storage interactions. The objective function posited in the original model considers solely the pipeline cost (and thus implicitly neglects the possibility to observe cost differences among the various storage sites) whereas total storage costs are explicitly accounted for in the objective function of the present model.

Hence, the solution to our model does not necessarily pair each cluster with the closest storage site: it can opt for the installation of a longer pipeline system if the extra pipeline cost is more compensated by a lower storage cost.

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[20] *It should be noted that the value of the parameter M is arbitrarily set at a level that is large enough for the constraint (B.5) to be non-binding whenever the pipeline is built and* δ_p*=1. In the present case, we assume that M equals 10 times the sum of the quantity of* CO_2 *injected at all nodes (i.e.,*$M = \sum_{i \in N} Q_i$*). Introducing that linear constraint provides important computational benefits. Without that constraint, one would have had to introduce the non-linear term* $\left[F_p^{pipe} + C_p^{pipe}(q_p^+ + q_p^-)\right]\delta_p$ *in the pipeline cost component of the objective function (B.1) which is logically equivalent but computationally far more challenging to solve. As the cooperative game theoretic analysis, that will be developed in this report requires solving a total of* 2^n *instances of that optimization model, we cannot overlook these computational issues. This type of linear reformulations is very popular in the operations research (O.R.) and modelling literatures and are usually nicknamed « big M » constraints in that community's jargon.*

[21] *Indeed, we assume that* x_N^* *is a solution and that there is at least one pipeline* p' *with* $q_{p'}^{+^*} > 0$ *and* $q_{p'}^{-^*} > 0$*, we consider the decision vector* x_N^{**} *where the pipeline flows are the net non-negative flows in each direction* $q_{p'}^{+^{**}} = max\left(q_{p'}^{+^*} - q_{p'}^{-^*}, 0\right)$*,* $q_{p'}^{-^{**}} = max(q_{p'}^{-^*} - q_{p'}^{+^*}, 0)$ *and the other variables have the same values as the ones in* x_N^**. By construction,* x_N^{**} *also verifies the constraints (B.2)-(B.7) while yielding a lower value for the objective function (B.1) because* $q_{p'}^{+^{**}} + q_{p'}^{-^{**}} = \left|q_{p'}^{+^*} - q_{p'}^{-^*}\right|$ *and thus* $C_{p'}^{pipe}\left(q_{p'}^{+^{**}} + q_{p'}^{-^{**}}\right) < C_{p'}^{pipe}\left(q_{p'}^{+^*} + q_{p'}^{-^*}\right)$*.Hence, we have a contradiction because* x_N^* cannot *be a solution of the optimization problem.*