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Capturing industrial CO_2 emissions in Spain: Infrastructures, costs and break-even prices

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Abstract

This paper examines the conditions for the deployment of large-scale pipeline and storage infrastructure needed for the capture of CO_2 in Spain by 2040. It details a modeling framework that allows us to determine the optimal infrastructure needed to connect a geographically disaggregated set of emitting and storage clusters, along with the threshold CO_2 values necessary to ensure that the considered emitters will make the necessary investment decisions. This framework is used to assess the relevance of various policy scenarios, including (i) the perimeter of the targeted emitters for a CCS uptake, and (ii) the relevance of constructing several regional networks instead of a single grid to account for the spatial characteristics of the Spanish peninsula. We find that three networks naturally emerge in the north, center and south of Spain. Moreover, the necessary CO_2 break-even price critically depends on the presence of power stations in the capture perimeter. Policy implications of these findings concern the elaboration of relevant, pragmatic recommendations to envisage CCS deployment locally, focusing on emitters with lower substitution options toward low-carbon alternatives.

Keywords: Carbon Capture and Storage; CO_2 pipeline network; Break-even price for deployment.

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1. Introduction

Carbon Capture and Storage (CCS)[1] is recurrently presented as a critically needed technology in long-term energy scenarios (e.g., IEA, 2017; Knopf et al., 2013)[2] because it *de facto* reconciles the existing dependence upon fossil fuels while making achievable the ambitious CO_2 abatement targets required for a 2°C-compatible world. However, CCS faces the reality of a slower-than-anticipated uptake. With few exceptions, to date, large-scale integrated CCS projects have not been commercially deployed, and skepticism regarding the future outlook of that technology (Banks and Boersma, 2015) is now increasing. In light of these difficulties, research examining the socio-economic barriers to the deployment of CCS and proposing adapted policy remedies is now gaining momentum.[3]

For policymakers, a crucial question mark remains to be addressed and provides the basic motivation for the present paper: what is the market price per ton of CO_2 that would be needed to trigger the adoption of CCS capabilities? To address it, our point of departure is the policy discussion in Herzog (2011) who called for further attention to be paid to the conditions needed for the construction of a large-scale CO_2 pipeline and storage infrastructure to be decided. So far, CO_2 infrastructure issues have predominantly been examined through the application of optimization techniques to identify the cost-minimizing design of an integrated CCS infrastructure network (Bakken and von Streng Velken, 2008; Middleton and Bielicki, 2009; Kemp and Kasim, 2010; Klokk et al., 2010; Mendelevitch et al., 2010; Kuby et al., 2011; Morbee et al., 2012; Oei et al., 2014; Oei and Mendelevitch, 2016). Yet, an examination of these prior contributions suggests two possible policy-relevant extensions.

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[1] *CCS is the integrated process of capturing CO_2 at large, stationary sources (e.g., thermal power plants, industrial sites) and storing it permanently in a suitable geological formation to prevent its release into the atmosphere.*

[2] *For example: in its latest Energy Technology Perspectives outlook (IEA, 2017), the International Energy Agency presents a 2°C scenario for which the contribution of CCS accounts for 14% (3rd position behind energy efficiency and renewable energy sources) of the additional abatements with respect to a reference scenario.*

[3] *In response to that situation, a rapidly burgeoning literature has recently investigated, among other topics: (i) the social acceptability and the public attitudes with respect to CCS infrastructures (Shackley et al., 2004; Riesch et al., 2013; Gough et al., 2014; Braun et al., 2017); (ii) the adapted R&D policies for the CCS technology (Eckhause, 2011; Eckhause and Herold, 2014); (iii) the design of the fiscal and regulatory incentives needed to foster the rapid and massive adoption of carbon capture capabilities (Comello and Reichelstein, 2014; Banal-Estañol et al., 2016).*

First, in most of these articles, the bulk of the emissions transported and stored is supplied by the power sector which is assumed to play a central role in the analysis. However, Hirschhausen et al. (2012) and Martinez Arranz (2015) question the usefulness of the deployment of carbon capture capabilities at thermal generation plants as alternative technologies (e.g., the installation of renewable energy sources) are likely to provide more affordable mitigation options. In contrast, CCS is critically needed to decarbonize other carbon-intensive industries for which there are no other abatement technologies (e.g., cement, iron and steel). As the future prospects for CCS in the power sector are jeopardized, there is a need to examine the economics of a less ambitious CCS deployment that would overlook the power sector and concentrate solely on the other industrial sectors. At first sight, one may infer that the absence of the power sector is likely to make the emergence of CCS even more complex as there will be a smaller volume of CO_2 over which to spread the large fixed costs of the pipeline infrastructure. That said, the exact nature of that effect and its magnitude still have to be documented.

Second, one can remark that the models used in these earlier contributions implicitly posit an idealized industrial organization whereby a unique decision-maker (e.g., a benevolent central planner) is assumed to have total control over the whole CCS chain. However, in reality, the creation of a large-scale CCS infrastructure with national scope is subject to the individual decisions to adopt carbon capture capabilities taken by a group of independent emitters. As these emitters are unlikely to strictly obey a “superior” decision-maker, a closer examination of the coordination issues faced by that collection of independent agents is needed. In a recent contribution, Massol et al. (2015) develop a cooperative game theoretic approach to investigate the conditions needed for a collection of emitters to share a common pipeline infrastructure and to determine the break-even price for CCS adoption. Yet, that prior analysis concentrates only on the simplistic case of a point-to-point pipeline system that connects the emitters in Le Havre to a unique storage site located near Rotterdam and posits that emitters have an unique outside option: laying an alternative pipeline along that route. However, in reality, one can envision the deployment of a meshed network infrastructure that has a more flexible morphology and on which one can hardly pair each emitter with a storage location.

The purpose of this paper is thus to examine the conditions for the deployment of a large-scale CO_2 infrastructure project aimed at transporting the CO_2 emissions captured at a series of industrial clusters to a series of storage sites where the CO_2 could be injected into a saline aquifer for permanent storage. To account for the difficulty in organizing the adoption of carbon capture capabilities in the energy sector, our analysis successively considers two scenarios that depend on whether the CO_2 emissions from carbon intensive industrial facilities (iron and steel, cement, pulp and paper) are supplemented or not by the volumes of CO_2 captured at thermal generation plants and oil refineries.

We consider Spain as a case study for our analysis because at least three distinct lines of arguments make it an interesting candidate. First, fossil fuels represent 85% of the Spanish primary energy supply, while the 240Mt of CO_2 emitted account for 7.5% of the EU28 total. As a member of the EU, Spain is fully committed to reaching the European objectives of reducing emissions by 40% in 2030 and 85% in 2050 with respect to the 1990 levels. Second, spatial considerations cannot be overlooked. While the North Sea oil fields are recurrently presented as a preferred destination for the CO_2 captured in Europe, the cost of routing the CO_2 captured in Spain to the trunkline systems envisioned in northern Europe would be prohibitive.[4] Third, a remarkable data set on emission sources and storage potentials has recently been assembled for that country under the auspices of COMET, a large project funded by the EU (Boavida et al., 2011, 2013; Kanudia et al., 2013).

The paper is organized as follows. Section 2 presents the Spanish case. Section 3 describes the determination of the least-costly CCS infrastructure and identifies three regional subsystems that could be independently deployed in Spain. Section 4 has a methodological nature and explains how the conditions for CCS adoption can be identified using cooperative game-theoretic notions. Section 5 discusses our assumptions regarding the cost of the carbon capture operations conducted at each cluster. Section 6 presents our results regarding the break-even prices for the deployment of the three regional subsystems and compares them with the values derived from traditional cost-engineering studies that do

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[4] *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 favor the deployment of an Iberian-centric CCS infrastructure that would remain physically disconnected from the northern European* CO_2 *pipeline systems.*

not take into account the existence of strategic interactions among players connected to a common infrastructure. The last section summarizes our conclusions and highlights the policy implications of our analysis. The detailed numerical assumptions retained for our analysis are presented in Appendix A. Appendix B presents the detailed specification of the optimization model used to support our analysis.

2. Background: The Spanish sources of CO_2 and potential sinks

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

2.1 The emission clusters under scrutiny

According to the European Pollutant Release and Transfer Register (E-PRTR) database,[5] a total of 144 large facilities are currently emitting CO_2 in mainland Spain[6] in 2014. This number is too large to follow the approach in Massol et al. (2015) that examines the plants' individual decisions to adopt carbon capture capabilities.[7]

Instead, we build upon the approach retained in the EU-funded COMET project and follow Boavida et al. (2011, 2013) who grouped emitters into clusters of reasonable size (see Appendix A). Our analysis thus considers 16 distinct clusters labeled E1 to E16 (see Table 1).[8] The map in Figure 1 illustrates their locations. It should be noted that, with the exception of the Madrid 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.

Table 1. The emission clusters

[PLEASE_INSERT_TABLE_1_HERE]

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[5] *See: http://prtr.ec.europa.eu/*

[6] *i.e.: Ceuta, Melilla, the Balearic and Canary Islands excluded.*

[7] *It would require an evaluation of the cost of installing an optimal CCS infrastructure for each of* $2^{144} \approx 2.23\times10^{43}$ *coalitions that can be formed by these 144 emitters, which is computationally out of reach.*

[8] *The correspondence between our clusters and the ones used in the COMET project is detailed in Appendix A.*

Figure 1. The geography of the emission clusters and the candidate pipelines and storage sites

[PLEASE_INSERT_FIGURE_1_HERE]

We consider the construction of a CCS infrastructure that is aimed at being operated during a 30-year planning horizon starting in 2040. This starting date is consistent with both the IEA's future global outlook for CCS which posits that the technology will be commercially available on that date (IEA, 2016); and the simulation results of the TIMES model developed under the COMET project that show that a mature CCS infrastructure will need to be installed in Spain on that date (Kanudia et al., 2013).

We investigate the possible future deployment of a CCS infrastructure in Spain through two scenarios. The first one is labeled "*All*" and posits that all the CO_2 that can be captured by the thermal power stations, the cement factories, the oil refineries, the pulp and paper plants, and the iron and steel industries at each of the 16 emission nodes will be captured. The second is labeled "*Indus_only*" and considers only the emissions from the cement factories, the pulp and paper plants, and the iron and steel industries at clusters where these industries collectively emit at least 1 $MtCO_2$/year.

Our motivations for considering the restricted scenario "*Indus_only*" that omits both the thermal generation plants and the oil refineries are threefold. Firstly, this scenario is consistent with the Spanish coal situation. In recent years, the government has begun to emphasize the need to organize an industrial reconversion of the mining areas, aiming for a gradual closure of the coal mines (Zafrilla, 2014).[9] As the Spanish coal mining industry is gradually disappearing, one wonders whether there will be a possible decline of coal-based power generation in the country. Secondly, the relevance of carbon capture technologies in the power sector is now being questioned because, in contrast to CCS, investment costs for renewables have experienced substantial cost decreases through higher learning effects which have made them a much cheaper abatement option (Hirschhausen et al., 2012; Martinez Arranz, 2015). In contrast, avoiding CO_2 emissions in the industrial sectors may be more important than in the electricity sector, because in some industries (e.g., cement, iron and steel) low-carbon substitute

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[9] *This is a notable change because, historically, via subsidies Spain facilitated the use of domestic coal in power plants to compensate its lack of competitiveness (as opposed to imports from other countries) and thereby protect employment in the Spanish mining regions (Rosal Fernández, 2000).*

technologies are more difficult to develop than in the electricity sector, and avoidance costs through the potential use of CCS may also be cheaper. Lastly, our decision to omit the refining sector is justified by the very high cost of equipping these industrial sites with carbon capture capabilities. An oil refinery represents a complex collection of carbon-emitting processing units that all have to be equipped with dedicated carbon capture equipment (Leeson et al., 2017). Compared to simpler industries like iron and steel or cement where the bulk of the CO_2 emissions generally come from one or two sources, the presence of a much larger number of small emission sources is reputed to make the implementation of carbon capture more technically challenging and expensive.

The "*Indus_only*" scenario thus echoes these recommendations to (i) abandon the aspiration of a broader deployment of CCS encompassing both the industrial activities and the energy industries, and (ii) follow a selective deployment aimed at "picking the low hanging fruit." This would be achieved by focusing solely on the heavy industries where carbon capture is both affordable, hardly substitutable, and the least costly mitigation option.

Our assumptions regarding the annual quantities of CO_2 that can be captured under the two scenarios are based on the simulation results of the TIMES model developed by Kanudia et al. (2013) for the COMET project[10] and were constructed as follows. We examine the simulation results of that model for the year 2040 in a mitigation scenario whereby the evolution of the EU energy system is obliged to achieve the EU-2020 targets as well as a 40% reduction of the domestic greenhouse gas emissions by 2050 relative to 1990.[11] These simulation results provide for each emission cluster the annual quantity of CO_2 that will be emitted by the electricity, pulp and paper, cement, refining, and iron and steel plants, respectively. Only a fraction of these emissions can be captured via CCS. In this study,

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[10] *We are grateful to Dr. Amit Kanudia (KanORS) for having kindly shared with us the detailed results of the numerous simulations he conducted for the COMET project.*

[11] *Oei and Mendelevitch (2016) retained a similar mitigation scenario for their analysis of the deployment of CCS. We have also considered a -80% scenario as this target provides the base working assumption used by the European Commission for decarbonizing the European economy. Yet, a detailed examination of the potential for CCS deployment obtained under the -40% and -80% scenarios in the simulation results prepared for the COMET project shows that, though the timing of the deployment differ under the two scenarios, the annual quantities of CO_2 captured after 2040 are similar. As we conduct a static analysis here for 2040 when the demands for CO_2 storage are similar under these two scenarios, we consider that focusing on the -40% scenarios is a reasonable assumption for this work.*

we use the sector-specific capture rates mentioned in Kanudia et al. (2013): 90% in the electricity and pulp and paper sectors, 85% in the cement and refining sectors, and 65% in the iron and steel sectors.[12] As we did not have access to the annual emissions trajectories after the year 2040, we assume that the emission data will remain steady over time.

The annual quantities Q_{ij} of CO_2 captured by the plants in each industrial sector j in each cluster i are detailed in Figure 2 where the color blue (respectively: red, green) is used for the thermal power plants (respectively: the oil refineries, the other industries).

Figure 2. The capture potentials Q_{ij} at each cluster under each scenario (in $MtCO_2$/year)

[PLEASE_INSERT_FIGURE_2_HERE]

Under the optimistic scenario "*All*," the total annual quantity that can be captured at these 16 clusters attains 112.7 $MtCO_2$/year which, according to the results of the TIMES-COMET model, represents about 60% of the nation's annual CO_2 emissions at stationary sources in 2040. The power sector (respectively, the refining sector) accounts for 39.7% (respectively, 8.9%) of that capture potential. Hence, it is interesting to highlight: (i) the important weight of the three other industrial sectors which together account for more than half of the total capture potential (58.0 $MtCO_2$/year), and (ii) among them, the large size of the cement sector that represents more than a third of the total capture potential (38.1 $MtCO_2$/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 7.0 $MtCO_2$/year but the two largest clusters (namely E2 – the cement plants and heavy industries in Asturias – and E7 the metropolitan area of Barcelona) together account for 24% of the overall capture potential whereas the two smallest clusters (namely E4 near Burgos and E16 near Santander) only capture 2.5% of that total.[13]

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[12] *Overall, one can observe that the capture rates posited in our study are consistent with the rates mentioned in a recent review of the techno-economic literature on carbon capture authored by a team of researchers and CCS experts at Imperial College (Leeson et al., 2017).*

[13] *One could thus wonder whether the two smallest clusters, E4 and E16, 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*

Under the restricted scenario "*Indus_only*," only 12 clusters have a capture potential larger than our 1 $MtCO_2$/year threshold. Accordingly, there is no need to consider the emission clusters located in Tarragona (E8), Cartagena (E11), Algeciras (E13), and Santander (E16) in that scenario. The cumulated capture potential of the industrial sites located at the 12 remaining clusters attains 55.2 $MtCO_2$/year, which represents 62.4% of the annual volume of CO_2 emitted by the Spanish pulp and paper, cement, and iron and steel sectors in 2040. The average quantity of CO_2 that can be captured at one of these 12 clusters is 4.9 $MtCO_2$/year but, again, the large integrated steel mill located in Asturias (E2) and the cement factories located near Barcelona (E7) and Madrid (E15) have a significantly larger capture potential.

2.2 Storage sites

Spain has a favorable geologic endowment in onshore saline aquifers. In a recent geoscience study, Carneiro et al. (2015) examine the techno-economic characteristics (i.e., volume, injection capacities, costs) of the underground structures that could be developed in Spain. Their results indicate that it is technically possible to accumulate up to 10.3 $GtCO_2$ without incurring a levelized cost of storage[14] larger than €7.2 per ton of CO_2 injected. Building on their analysis, the present study considers the eight cost-effective candidate storage sites mentioned in Figure 1 and listed in Table 2. That table reveals that there are substantial variations in both the capacities and costs of the storage sites. This variability reinforces the need to account for storage costs in our infrastructure planning model.[15] Indeed, a simple pairing of the CO_2 sources with the closest storage site may be neither feasible nor economically efficient.

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transportation corridors that exist in northern Spain, which suggests that the incremental cost of getting them connected to a pipeline infrastructure should remain reasonable. (cf. Figure 1).

[14] *The levelized cost of storage is calculated as the net present value of all costs over the planning horizon (i.e., our 30-year period) divided by the present value of the quantities injected over that period. The levelized cost of storage is the constant euro storage price that would be required over the 30-year period to cover all capital expenditures, subsequent periodic operating expenses, and the payment of an acceptable return to investors. It should be noted that these cost figures are based solely on technical considerations and thus omit the possibly substantial (but hard to evaluate ex ante) cost of the measures needed to make a storage project socially acceptable by the local population. In case of strong local opposition, that cost would become prohibitive and would impose the use of another storage site.*

[15] *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.*

Table 2. The maximum injection rates and costs of the candidate storage sites

[PLEASE_INSERT_TABLE_2_HERE]

2.3 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, we consider a predefined list of 49 candidate pipelines (cf. Appendix A) that could be installed to connect the emission clusters nodes E1 to E16 with the candidate storage nodes S1 to S8. From that list of candidate pipelines, it is possible to build a realistic network that accounts for Spain's mountainous geography (terrain, landforms, natural transportation corridors). As shown in Figure 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 ($tCO_2 \times 100$ km). As indicated in Appendix A, 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 ($tCO_2 \times 100$ km). In our analysis, we use a value of €1.5 per ($tCO_2 \times 100$ km).

3. Optimal deployment of CCS infrastructure in Spain

In this section, we first examine the least-cost design of CCS infrastructure aimed at storing the quantities of CO_2 captured under the two scenarios. Then, we investigate whether the Spanish infrastructure has to be analyzed as a unique integrated national infrastructure or whether it can be decomposed into a collection of regional subsystems.

3.1 The least-costly infrastructure deployment

We have formulated an optimization problem aimed at determining the least-costly design of a CCS infrastructure capable to transport and store the CO_2 captured at the Spanish clusters. This model is formally described in Appendix B. It aims at choosing the pipelines and storage sites (among our predefined and finite list of candidate pipelines and storage sites) that minimize the total annual equivalent cost of building and operating the pipeline and storage infrastructure. More precisely, we adopt a static framework for the year 2040. In that year, the total national demand for capturing CO_2 and hence the annual storage requirement is imposed by our assumption. 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 (eventually 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 2040-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 the above-mentioned input data to identify the ideal CCS infrastructure under our two capture scenarios. The results are illustrated in Figure 3.

Figure 3. CO_2 pipeline and storage deployment in Spain

[PLEASE_INSERT_FIGURE_3_HERE]

At first sight, one could conjecture from the figures detailed below the two maps that the total annual equivalent costs of the infrastructure per unit of CO_2 transported are similar in the two scenarios and thus conclude that the total annual equivalent costs of the infrastructure is directly proportional to the total flow transported. Yet, that first impression is misleading because there are marked differences in the cost structure of the two CCS systems. The pipeline cost figures reveal the presence of important economies of scale: the annual volume of CO_2 transported in the scenario "*All*" is twice as large as the one in "*Indus_only*" though the pipeline cost is only 66% percent larger. This result is not surprising as the total lengths of the networks are similar, which suggests that fixed pipeline costs are spread out over more units of output under the scenario "*All.*" In contrast, one can observe that the total storage cost is 2.77 times larger under the scenario "*All*" as its extra volume of CO_2 saturates the capacity of the least costly storage sites and imposes a mobilization of the more expansive ones in S1 and S8.

From a comparison of these two maps, several findings can be highlighted. First, whatever the scenario under scrutiny, the optimization model does not recommend the construction of a fully-connected national pipeline system but rather prefers the construction of a fragmented collection of pipelines that are physically disconnected. Second, the morphology of some of these pipeline connections is scenario dependent. In the north, the clusters located at Leon (E3) and Burgos (E4) either form an independent infrastructure or are embedded within a larger northern infrastructure. A similar observation can also be made for the clusters near Valencia (E10) and Almeria (12). The emissions captured in Aragon (E9) are either stored in S2 together with the ones captured along the Atlantic coast (cf., scenario "*Indus_only*") or are directed to S3 where the CO_2 captured in Catalunya (E7, E8) is also directed (cf., scenario "*All*"). Hence, the optimal infrastructure deployment decided for the northern emission nodes and the ones located in Catalunya may not be independent. In contrast, the CO_2 captured by the emitters located in the Madrid-La Mancha area (E15) is systematically routed to the neighboring storage S4 located in Cuenca, and that storage site only receives CO_2 from that cluster. One may thus wonder if a CCS deployment in E15 could be organized independently from what is decided in the other clusters.

3.2 Regional subsystems

From the graphical insights above, one could conjecture that it may be possible to decompose the national infrastructure into a collection of independent subsystems, that is, subsets of emissions, transit, and storage nodes that interact with each other to organize the CCS chain – sharing costs and possibly connecting to each other, irrespectively of the choices made in other regions of the peninsula. To formally investigate this proposal and determine the boundaries of these regional subsystems, we successively consider the coalitions listed in Table 3. Each of these coalitions represents a candidate subsystem of emission areas that could potentially be separated from the national system.

Table 3. The subsystems of emission clusters under scrutiny

[PLEASE_INSERT_TABLE_3_HERE]

For an emissions-transit-storage nodes subsystem, call it S, to be analyzed independently of the rest of the national system, we need to make sure that it does not interact with any other subgroup. From a cost perspective – and as described in the cost optimization model in Appendix B, this means that none of these other subgroups should be willing to join S in the course of satisfying its demand for storage because it would reduce its average cost of serving the demand. In other words, none of the costs of serving S plus another subset should be strictly subadditive, so that no economies of scale can emerge from sharing.

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 coalitions 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 $i \in N \setminus S$), 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., $S' \subset N \setminus S$). 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 $N \setminus S$ and letting $|N \setminus S|$ denote the number of elements in $N \setminus S$, a total of $2^{|N \setminus S|} - 1$ incremental costs have to be evaluated for each coalition S. If for a given coalition S and any coalition S' in $N \setminus S$, 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 $2^{|N \setminus S|} - 1$ equality conditions hold, there are no cost interactions between the emission clusters in S and the others in $N \setminus S$ and one can separately examine the deployment of a CCS infrastructure aimed at solely serving S without paying attention to the other emission clusters.

These cost comparisons[16] reveal that, among all the candidate subsystems listed in Table 3, only three verify the conditions for a separable cost function: (i) all the nodes located onshore on the Atlantic coast, and the ones in Castilla-León, Aragon, and in the Mediterranean regions of Catalunya and Valencia, $\{\mathrm{E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E16}\}$, (ii) all the nodes located in the southern regions of Murcia and Andalucía $\{\mathrm{E11, E12, E13, E14}\}$, and (iii) the emission cluster located in the Madrid-La Mancha area $\{\mathrm{E15}\}$. In the sequel, we thus partition the set of Spanish emission clusters into these three subgroups and independently examine the conditions for the deployment of three autonomous CCS infrastructures that are respectively labeled: North, South and Central. An illustration of that decomposition is presented in Figure 4.

Figure 4. An illustration of the three independent subsystems

[PLEASE_INSERT_FIGURE_4_HERE]

The annual volumes of CO_2 captured and stored at each infrastructure and the associated infrastructure cost under the two scenarios "*All*" and "*Indus_only*" are detailed in Table 4. The northern infrastructure has by far the largest potential for CO_2 abatement. A rapid division of the total infrastructure cost by the volume of CO_2 captured and stored provides the average transportation and storage cost. These figures indicate that the central infrastructure, which gathers a unique emission cluster, also has the lowest unit cost (less than 7€/tCO_2 p.a. compared to figures larger than 9.3€/tCO_2 p.a. for the other infrastructures).

Table 4. The three independent infrastructure systems

[PLEASE_INSERT_TABLE_4_HERE]

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[16] *Results are available from the corresponding author upon request.*

4. Methodology: A cooperative game theoretic framework

In this section, we first provide a non-technical presentation of our cooperative game-theoretic framework. Then, two subsections detail the conditions that have to be verified for the construction of a common infrastructure to be decided. Lastly, we define the break-even CO_2 price for joint CCS adoption and show how it can be evaluated.

4.1 Cooperative game and stability notion

We consider a regional subsystem of emission clusters, like the ones identified in the preceding section, and examine the conditions for the construction of the least-cost (not necessarily fully-connected) CCS infrastructure in that subsystem, also identified in the previous section.

Hereafter, N refers to the grand coalition joining all the emission clusters in that subsystem: either $N = \{\mathrm{E11, E12, E13, E14}\}$ in the southern region, $N = \{\mathrm{E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E16}\}$ in the northern region or $N = \{\mathrm{E15}\}$ in the central one.

By nature, a CO_2 pipeline and storage system is a mutualized infrastructure and its cost must be apportioned between all the individuals that feed CO_2 into that system. In this paper, we assume that each emission cluster represents an autonomous decision-making entity that can either feed all the volumes of CO_2 captured by the local emitters to the grand infrastructure, feed them to a different infrastructure or renounce CO_2 capture. The arrangements guiding the internal functioning of that emission cluster will be further discussed below. For the moment, we simply overlook that issue and treat all the emitters in a given emission cluster as a monolithic agent, that is, as an individual player.

Following the cooperative game theoretic approach in Young (1985), the players are considered to negotiate with each other to determine a binding agreement between them regarding the sharing of the total cost of building and operating the grand infrastructure. To examine the different possibilities within a game for cooperation among players, we must evaluate what cost can collectively be incurred by any subgroup of players S in the set N. Indeed, if a certain subgroup of players assesses that it pays more than it could do by itself then this group may abandon the negotiations with the other players and opt for a stand-alone attitude (i.e., develop its own infrastructure). Our ambition is thus to identify whether or not it is possible to share the total cost of the grand infrastructure in such a manner that no subgroup of players has an incentive to disband. Such a cost allocation is said to belong to the "core" of the cost game.

We shall now specify what a given coalition S can achieve if it decides to opt out from the grand coalition and build an infrastructure aimed solely at serving its own needs. To do so, one should first examine the economic features of the shared elements of the CCS supply chain: the pipeline network and the storage site. Regarding transportation, the technology used in CO_2 pipelines is not proprietary. Potentially, several pipeline firms may have access to the same technology and may install a pipeline system between a group of emission clusters and some storage sites. In contrast, excludability can be at work on the storage side. At a given storage site, the quantity of CO_2 that can be injected by S plus the total volume injected by the other emission clusters in $N\backslash S$ cannot exceed the capacity constraint of that storage. Such a capacity constraint creates a mutual influence among coalitions, a feature called an externality among coalitions. In the presence of externalities, the players who are about to deviate must take into account the behavior of the remaining agents because the cost incurred by the deviating coalition – thus the incentive to disband – can vary with the decisions taken by these remaining agents.

Several options can be envisaged to determine the cost incurred by a deviating coalition S that varies with the behavior posited for the remaining agents in $N\backslash S$. Most of the literature on cooperative game theory in the presence of externalities makes one of the following two extreme assumptions. Some papers assume that non-deviating members would stay together (e.g., Horn and Persson, 2001) whereas others assume that they would split apart (e.g., Barros, 1998; Chander and Tulkens, 1997).[17] In this paper, we take the first approach because we think it is more likely that the remaining coalition members would build a joint infrastructure than they would build many, separate ones independently. The remaining members of the grand coalition are more likely to have assessed the feasibility of a joint project (including geoscience studies, pipeline routing analyses, permitting procedures).

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[17] *Very few papers consider the optimal reaction of the non-deviating coalition members (an exception involving a game with only three players is Banal-Estañol et al., 2008).*

We use this observation to model the strategic behavior between the two coalitions ($N \backslash S$ and S). We assume that the remaining players in the grand coalition (i.e., the ones in $N \backslash S$) collectively conserve a first-mover advantage. That is, they can decide the construction of the least costly CCS infrastructure aimed at serving their own needs without taking into account the volume injected by the other emission cluster in the storage capacity constraint.

We implement these assumptions as follows. First, we determine the optimal transport and storage decisions of the remaining coalition $N \backslash S$ by solving an instance of the optimization problem in Appendix B where the annual emissions captured by the deviating clusters are $Q_i = 0$ for all i in S. The solution of that mathematical programming problem provides the decision vector chosen by $N \backslash S$ and thus the quantities injected at each storage site. Then, we assume that the deviating coalition S observes the injection decisions of its complement $N \backslash S$ and takes them as given by playing its best response to these injection decisions.[18] By replicating that two-stage numerical procedure for each of the $2^{|N|} - 2$ coalitions S with $S \subset N$ and $S \neq \emptyset$ and $S \neq N$ that can be formed, we are able to determine the cost $C^*(S)$ that would be incurred by a deviating coalition S.[19] To ease the notation, we also let $C^*(N) = C(N)$.

4.2 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 $r = \left(r_1, ..., r_{|N|}\right)$ where r_i is the amount charged to the emission cluster i, denote the revenue vector

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[18] *Technically, this is done by solving an adapted version of the optimization problem in Appendix B where the annual emissions captured by the remaining clusters are set to zero (i.e., $Q_i = 0$ for all i in $N \backslash S$) and the capacity level at each storage site is the difference between the physical capacity and the quantity already injected by the remaining players in $N \backslash S$.*

[19] *Note that this procedure is computationally demanding because, for each deviating coalition S, it requires to sequentially solve two instances of the mixed integer linear programming problem presented in appendix B: one to determine the behavior of the complement coalition and one for the deviating coalition.*

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:

$$\sum_{i\in N} r_i = C^*(N). \tag{1}$$

Each coalition of emission clusters S compares: $\sum_{i\in S} r_i$ 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:

$$\sum_{i\in S} r_i \le C^*(S), \qquad \forall S \subset N,\ S \notin \{\varnothing, N\}. \tag{2}$$

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 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.

4.3 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 $\left(p_{CO_2} - \chi_i\right)Q_i$ represents its willingness to pay for a CO_2 pipeline and storage service and, thus, the amount $\left(p_{CO_2} - \chi_i\right)Q_i - r_i$ 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.:

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

4.4 The break-even price for joint CCS adoption

The analysis in Massol et al. (2015) shows that the condition for the pipeline operator to be able to build the grand infrastructure amounts to set a revenue vector that verifies conditions (1), (2), and (3). The prevailing carbon price has a direct influence on the individual net benefit of the emission clusters and thus on the possibility for the infrastructure operator to determine such an incentive-compatible revenue vector. We thus define $p_{CO_2}^*$ the break-even price for joint CCS adoption as the critical value in the charge for CO_2 emissions that would be compatible with the satisfaction of the three conditions. This break-even price is the solution of the following linear program LP1:

LP1:

$$\min_{r, p_{CO_2}} \quad p_{CO_2} \tag{4}$$

$$\text{s.t.} \quad \sum_{i \in N} r_i = C^*(N), \tag{5}$$

$$\sum_{i \in S} r_i \le C^*(S), \qquad \forall S \subset N \setminus \{\varnothing, N\}, \tag{6}$$

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

5. Data: The cost of the carbon capture operations

5.1 Data: The unit capture costs of the industrial sectors

The cost to build and operate carbon capture equipment is specific to each industrial sector (Leeson et al., 2017). In this paper, we assume the unit capture costs listed in Table 5 that are based on recent cost engineering analyses. These figures confirm that CO_2 capture is extremely expensive in the oil refining sector. In the other industrial sectors, the magnitude of the capture cost is commensurate with the ones observed in the power sector.

Table 5. The sector-specific capture costs

[PLEASE_INSERT_TABLE_5_HERE]

5.2 Cluster agreements and average vs. marginal costs

We consider two extreme assumptions regarding the arrangement guiding the internal functioning of the emission clusters. We first assume that transfers between individual plants in each cluster are feasible. In this case, the individual plants of each cluster will consider the average costs of the plants in the cluster and the overall gains to the cluster in any given coalition, as side payments can be made from the lowest to the highest cost plants to compensate the plants with higher costs. Under that first assumption, χ_i the unit cost of the carbon capture operations conducted at cluster i is defined as the volume-weighted average capture cost at that cluster:

$$\chi_i = \frac{\sum_j Q_{ij} \chi_{ij}}{\sum_j Q_{ij}}. \tag{8}$$

where Q_{ij} is the annual quantity of CO_2 captured by the plants in industrial sector j in cluster i.

As side payments can be difficult to organize, we also consider a second assumption without transfers. In this case, the highest cost plant will be key as the gains obtained by any plant will need to compensate its costs. We are de facto assuming that each individual plant has veto power in the cluster. Under that second assumption, χ_i the unit cost of the carbon capture operations conducted at cluster i is thus defined as follows:

$$\chi_i = \operatorname*{Max}_j \chi_{ij}. \tag{9}$$

Of course, the reality is somewhere between these two extremes. Still, the differences between them will help us understand how crucial side payments are to the deployment of CCS in Spain.

5.3 The unit capture cost at each industrial cluster

Using the unit costs listed in Table 5, in each cluster we constructed the merit order of the local carbon capture units to calculate the unit capture cost χ_i at each industrial cluster under the two scenarios: "*All*" and "*Indus_only*." We successively use the two alternative assumptions presented above: χ_i is either defined as the volume-weighted average capture cost at that industrial cluster, or the unit capture cost observed at the plant that has the most expansive carbon capture technology among all the plants in the industrial cluster. These figures are detailed in Table 6.

Observe that in some clusters the difference between the two approaches retained to evaluate the capture costs can be substantial. This difference is particularly salient under the scenario "All" for all the clusters with oil refining activities $(\mathrm{E1}, \mathrm{E5}, \mathrm{E8}, \mathrm{E10}, \mathrm{E11}, \mathrm{E13}, \mathrm{E14})$. At these clusters, the non-oil-refining sectors will perceive large infra-marginal rents if these players refuse to organize some side payments but that strategy also conveys the risk of substantially raising the break-even price of CO_2 needed for the construction of the infrastructure.

Table 6. The unit capture cost χ_i at each cluster

[PLEASE_INSERT_TABLE_6_HERE]

6. Results and discussion

We now use these unit 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. For each scenario ("*All*", "*Indus_only*") and each candidate infrastructure (North, Central, South), we run two instances of the linear programming problem LP1: one assuming that the unit capture cost at each industrial cluster is based on the quantity-weighted average value, and one assuming that this cost equals the marginal value, as shown in equations (8) and (9). The results are presented in Table 7.

Table 7. The break-even price for CCS adoption $p^*_{CO_2}$ (€/tCO$_2$)

[PLEASE_INSERT_TABLE_7_HERE]

These results convey a series of interesting findings. First, one can compare the break-even prices obtained under the two scenarios for a given assumption regarding the unit capture costs. Interestingly, the break-even prices are slightly lower under the "*Indus_only*" scenario despite substantially lower volumes of CO_2 over which the fixed costs of the network and storage infrastructure can be spread. This is an important finding as it suggests that CCS can remain a competitive decarbonization option even if the power sector massively opts for renewable energy sources and thus abandons the carbon capture technology. Of course, this result also suggests to concentrate on the “low hanging fruits” by selecting only the industries where the installation of carbon capture technologies is affordable (i.e., by omitting the oil refining sector).

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 and south subsystems that gather several emission clusters. This is particularly true for the scenario in which all plants are included (“*All*”), and in the case of a no-transfer agreement (“marginal”).

Third, as can be expected again, one can note that under a given scenario the break-even prices are a bit lower for the quantity-weighted case, as it avoids the veto power of the highest cost plant. It is interesting to highlight that the magnitude of the difference between the marginal and quantity-weighted cases is substantially smaller under the scenario “*Indus_only.*” By construction, this finding is a direct consequence of the unit capture costs listed in Table 6, yet it suggests that the detailed outcomes of the internal bargaining conducted within each cluster are likely to play a less important role under the scenario “*Indus_only.*”

As a side remark, we note that there is no difference between the marginal and quantity-weighted price in the north subsystem in the “*Indus_only*” scenario. For that specific scenario, we have closely examined the two solutions of the linear program LP1. By construction, the solution of LP1 is such that at least one of the nine constraints (7) – recall that they state that the individual net benefit of each emission cluster must be non-negative – must be binding. Interestingly, in both cases, there is a unique binding constraint: the one associated with the emission cluster E1 located in A Coruña in Galicia. Under the scenario “*Indus_only,*” there is only one industrial sector in that cluster (an iron and steel plant – see Figure 2) which explains why the unit capture cost at that cluster equals 57.5€/tCO_2 both under the volume-weighted average and marginal methods. The difference between the break-even price and that unit capture cost reveals that a unit amount of 25.12€/tCO_2 is charged to this cluster by the infrastructure operator when the prevailing carbon price equals $p^*_{CO_2}$. This figure is far larger than the average cost of the infrastructure: 442/41.9 ≈ 10.55€/tCO_2 suggested from the figures in Table 4. A closer examination of the solution of LP1 reveals that this figure is exactly equal to the incremental cost that E1 imposes on the other emission clusters in the north. Hence, this is the lowest amount that can be charged by the pipeline operator without creating an opportunity for the other emitters to disband. By the way, a quick look at the location of that cluster on the map presented in Figure 4 suggests that this large incremental cost is not so surprising given the relatively small size of that cluster and its remote location (relative to those of the storage site S2).

Beyond the somehow anecdotal nature of that discussion centered on the case of the cluster E1, this analysis strongly questions the validity of the simple accounting-based or 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) and implicitly presume that this figure can be interpreted as the critical price of CO_2 required to trigger the construction of the CCS infrastructure. For example, Table 8 reports two values that could be retained in these simple cost-engineering studies that overlook the complex cost interactions which exist in an infrastructure that has network characteristics. These values are: (i) the simple average cost of the infrastructure (to reflect the case where internal bargaining can be conducted within the clusters), and (ii) the sum of the unit capture cost at the most expensive plant connected to the infrastructure plus the average cost of the pipeline and storage infrastructure (to reflect the case where side-payments cannot be implemented within the clusters). While the average cost and highest capture costs are representative of the break-even price for the simple, mono-node infrastructure Central, this is clearly not the case when one considers the more complex infrastructures of North and South. For these infrastructures, the difference with the break-even price $p^*_{CO_2}$ is substantial and the figures derived from simple accounting reasoning substantially underestimate the true break-even price capable of creating the conditions for a cooperative adoption of the CCS technology by all the emission clusters connected to the infrastructure. This means that not taking into account the strategic incentives may lead to a significant underestimation of the difficulties of deploying a CCS infrastructure that connects several emission sources.

Table 8. The simple cost metrics derived from accounting reasoning (€/tCO$_2$)

[PLEASE_INSERT_TABLE_8_HERE]

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. Previous research on that issue has two limitations that together provide the motivation for the present paper, namely (i) the potential failure of a widespread adoption of CCS in power generation and oil refining sectors, as well as (ii) the need to account for the coordination of actors along the chain to ensure a viable and mutually agreed cooperation at the regional level. This paper thus adopts a spatial approach to clarify the conditions that make the construction of a common pipeline and storage infrastructure with network characteristics a rational move for a set of regional clusters of industrial emitters that could be connected to that infrastructure. It also examines whether these conditions differ or not depending on the installation of carbon capture capabilities in the energy sector (i.e., at power plants, at oil refineries).

Taking Spain as a case study, the paper examines the least costly deployment of a national CCS infrastructure under these two scenarios. A closer analysis of their cost structures (i.e., on the separability of the cost function) reveals an important finding: this national infrastructure can be decomposed into three regionally distinct subsystems located in the north, center and south of Spain, meaning that under no circumstance of the scenarios under scrutiny does a pipeline link any pair of these regions. As these subsystems can be deployed independently, there is no need to concentrate the policymakers' attention on the construction of a grand infrastructure with national scope, but rather a regional approach with respect to the implementation of CCS should be favored.

The paper 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. A comparison of these break-even prices provides a series of interesting findings from a policymaking perspective. Firstly, the non-adoption of CCS technologies in the energy sector does not make the cost of CCS prohibitive. Accordingly, the current lack of progress of CCS in the energy sector should not discourage its implementation in the other industrial sector (provided sufficient incentives can be set). Secondly, we found that the internal bargaining conducted within each cluster regarding the sharing of the carbon capture cost plays a less important role when the infrastructure stores solely the CO_2 captured at industrial sites (i.e., when the energy sector is not present). We believe that this finding results from a greater homogeneity of the sector-specific costs to implement carbon capture capabilities. Lastly, this analysis calls for further attention to be paid to the network characteristics of the CCS supply chain when trying to infer the break-even price of these infrastructures. Indeed, preliminary cost-engineering studies based on average cost concepts may substantially underestimate the true break-even price.

As in any modeling effort, we made simplifying assumptions. We, for instance, neglected the role of uncertainty regarding CO_2 prices. As investments in carbon capture capabilities are irreversible, the presence of uncertainty can influence the emitters' individual decisions and thus the feasibility of a shared infrastructure. Risk-averse owners may thus require a higher premium to compensate for the risk of the investment. Further research could explore whether individual decisions based on a real-options framework can be combined with the cooperative game theoretic approach presented in this manuscript to gain further insights into the development of a CCS infrastructure. Incorporating the system effects of individual decisions (and thus the interactions) within a real-option framework, though, can be a challenging task.

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Appendix A – Emission clusters and candidate pipelines

The emission clusters

We build upon the results gained from the EU-funded COMET project to group emitters into clusters of reasonable size. From a database including the technical characteristics and geographical location of the Spanish stationary sources that emitted more than 0.1 Mt CO_2/a during the years 2005–10, the COMET team conducted an exhaustive clustering exercise that resulted in the identification of 56 sources of CO_2 in Spain that aggregate the emissions of the neighboring industries and power plants. They then simulated the future emission trajectories of each of these industrial sectors, using a detailed integrated bottom-up model of the Iberian energy system based on the TIMES framework (Kanudia et al., 2013). From their simulation results,[20] it appears that 23 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. As some of these sources are geographically very close, we have further regrouped them into 16 distinct clusters labeled E1 to E16. The following table clarifies the construction of our industrial clusters from the sources of CO_2 considered in the COMET project.

Table A.1. Correspondence between our industrial clusters and the sources of CO_2 used in the COMET project

[PLEASE_INSERT_TABLE A.1_HERE]

The candidate pipelines and their costs

Definition

Each pipeline connects two of 37 nodes: the 16 emission clusters nodes E1 to E16, the eight storage nodes S1 to S8 and the 13 intersection nodes labeled R1 to R13 that are listed in Table A.2. 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.

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[20] *We are grateful to Dr. Amit Kanudia (KanORS) for having kindly shared with us the detailed results of the numerous simulations he conducted for the COMET project.*

Table A.2. The intersection nodes

[PLEASE_INSERT_TABLE_A.2_HERE]

Table A.3. presents the candidate pipelines, their lengths and the dimensionless average terrain-correction factors τ that will be needed to evaluate the transportation costs. In our study, the average terrain correction factors were obtained by associating each kilometer of pipeline with the values indicated in IEAGHG (2002): e.g., 1.5 for mountainous terrain, 1.1 for agricultural land.

Table A.3. The candidate pipelines

[PLEASE_INSERT_TABLE_A.3_HERE]

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: $(A_0 + B_0 q)\tau$, where $A_0 = 4.6045$ is the fixed cost coefficient (in million 2015 euros),[21] the variable cost coefficient is $B_0 = 0.1641$ in 2015 euros per (t$CO_2$$\times$100 km) and τ is the average terrain correction factor described in IEAGHG (2002) and detailed in Table A.2.

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[21] *Original monetary values are in 2010 euros and were corrected for inflation to obtain 2015 euros.*

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.

Notation

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

- $N=\{1,...,i,...,|N|\}$ the set gathering the clusters where the captured emissions are injected into the network;
- $K=\{1,...,k,...,|K|\}$ the set gathering the storage nodes where CO_2 is withdrawn from the network to be injected in a saline aquifer;
- $R=\{1,...,r,...,|R|\}$ 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: $N\cap K=\varnothing$, $K\cap R=\varnothing$ and $N\cap R=\varnothing$. For notational convenience, we also let $\mathrm{Z}=N\cup K\cup R$ denote the macro-set regrouping all the nodes and z is used as a generic notation for a given node in Z. We also let $P=\{1,..., p,...,|P|\}$ 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;
- $\overline{Q}_k$ is the maximum amount of CO_2 that can be withdrawn from the network to be injected into storage k;

- $I_{p,z}$ 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_k^{inj} is the unit cost of the CO_2 injection operations conducted at storage k;
- 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., $\delta_p = 0$);
- 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_k^{inj} is the non-negative quantity injected into storage k.

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

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:

$$\underline{\text{MILP1:}} \quad \underset{x_N}{\text{Min}} \quad \sum_{p\in P}\left[F_p^{pipe}\delta_p + C_p^{pipe}\left(q_p^+ + q_p^-\right)\right] + \sum_{k\in K} C_k^{inj} q_k^{inj} \tag{B.1}$$

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

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

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

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

$$q_k^{inj} \le \overline{Q}_k\ , \qquad \forall k\in K\ , \tag{B.6}$$

$$q_k^{inj} \ge 0\ , \qquad \forall k\in K \ \text{ and } \ \delta_p\in\{0,1\}\ ,\ q_p^+ \ge 0\ ,\ q_p^- \ge 0\ ,\ \forall p\in P\ . \tag{B.7}$$

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.[22] The constraints (B.6) represent the sink injectivity constraints: at each storage node, the quantity injected cannot exceed the local injection

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[22] *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* $\delta_p = 1$*. 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* $\left[F_p^{pipe} + C_p^{pipe}\left(q_p^+ + q_p^-\right)\right]\delta_p$ *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 paper requires solving a total of* 2^n *instances of that optimization model, we cannot overlook these computational issues. This type of linear reformulations are very popular in the operations research (O.R.) and modeling literatures and are usually nicknamed « big M » constraints in that community's jargon.*

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.[23]

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 during 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 than compensated by a lower storage cost.

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23 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* $q_{p'}^{+**} = \max(q_{p'}^{+*} - q_{p'}^{-*}, 0)$, $q_{p'}^{-**} = \max(q_{p'}^{-*} - q_{p'}^{+*}, 0)$ *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.*

Table 1. The emission clusters

Label	Location	Region	Label	Location	Region
E1	A Coruña	Galicia	**E9**	Zaragoza	Aragón
E2	Oviedo-Gijón	Asturias	**E10**	Valencia	Valencia
E3	León	Castilla-León	**E11**	Cartagena	Murcia
E4	Burgos	Castilla-León	**E12**	Almería	Andalucía
E5	Bilbao	Euskadi	**E13**	Algeciras	Andalucía
E6	Pamplona	Navarra	**E14**	Huelva	Andalucía
E7	Barcelona	Catalunya	**E15**	La Mancha	Castilla–La Mancha
E8	Tarragona	Catalunya	**E16**	Santander	Cantabria

Table 2. The maximum injection rates and costs of the candidate storage sites

Cluster	Cluster name	Region	Storage volume ($MtCO_2$)	Maximum injection rate ($MtCO_2$/a)	Levelized storage costs (investment and O&M) (€/tCO_2)
S1	Aranda de Duero	Castilla-León	568	10.3	6.83
S2	Logroño	Rioja	4,161	35.7	3.36
S3	Alcañiz	Aragon	2,040	75.8	7.16
S4	Cuenca	Castilla-La Mancha	1,035	16.5	4.03
S5	Almansa	Castilla-La Mancha	959	15.5	2.69
S6	Moratalla	Murcia	413	7.3	1.57
S7	Ubeda	Andalucía	1,082	25.5	1.57
S8	Reinosa	Cantabria	54	1.7	6.94

Source: Carneiro et al. (2015). Levelized cost are evaluated for a 30-year injection period assuming a steady rate of injection and a real discount rate of 7 percent. Original monetary values are in 2007 euros and were corrected for inflation to obtain 2015 euros.

Table 3. The subsystems of emission clusters under scrutiny

Name of the candidate subsystem	Nodes
All the nodes located onshore the Atlantic coast, and the ones in Castilla-León, Aragon, and in the Mediterranean regions of Catalunya and Valencia.	{E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E16}
All the nodes located in the southern regions of Murcia and Andalucía.	{E11, E12, E13, E14}
All the nodes located in the Catalunya and Aragon regions.	{E7, E8, E9}
All the northern nodes located along the Atlantic coast.	{E1, E2, E16, E5, E6}
The Madrid-La Mancha area alone.	{E15}
The Valencia area alone.	{E10}
The Murcia region alone.	{E11}
The Almeria area alone.	{E12}
The Madrid-La Mancha area alone.	{E15}

Table 4. The three independent infrastructure systems

Infrastructure	Scenario “All”		Scenario “Indus_only”	
	Total volume of CO_2 captured and stored ($MtCO_2$/year)	Total annual equivalent cost (in million euros)	Total volume of CO_2 captured and stored ($MtCO_2$/year)	Total annual equivalent cost (in million euros)
Central	9.2	63.0	8.0	55.8
South	24.9	233.5	7.5	88.9
North	78.6	864.3	41.9	442.0

Table 5. The sector-specific capture costs

Sector	Unit capture cost (€/tCO_2)	Source
Cement	29.6	Leeson et al. (2017)
Iron & Steel	57.5	Leeson et al. (2017)
Pulp & Paper	44.3	Leeson et al. (2017)
Oil refining	96.3	DNV (2010)
Coal Power Plant (supercritical pulverized coal)	36.0	Rubin et al. (2015)
Natural Gas Power Plant	51.0	Rubin et al. (2015)

Note: The original values are in US dollars and have been converted into 2015 euros using the mean annualized exchange rate obtained from the International Monetary Fund.

Table 6. The unit capture cost χ_i at each cluster

		Scenario "All"		Scenario "Indus_only"	
Cluster Label	**Cluster name**	**Volume-weighted approach (€/tCO$_2$)**	**Highest cost approach (€/tCO$_2$)**	**Volume-weighted approach (€/tCO$_2$)**	**Highest cost approach (€/tCO$_2$)**
E1	A Coruña	57.22	96.30	57.50	57.50
E2	Oviedo-Gijón	45.06	57.50	47.34	57.50
E3	Leon	35.35	51.00	29.60	29.60
E4	Burgos	37.06	57.50	31.69	57.50
E5	Bilbao	59.62	96.30	34.99	57.50
E6	Pamplona	38.64	57.50	37.66	57.50
E7	Barcelona	34.63	57.50	32.22	57.50
E8	Tarragona	78.44	96.30	#	#
E9	Zaragoza	40.18	51.00	39.97	44.30
E10	Valencia	42.43	96.30	29.60	29.60
E11	Cartagena	49.60	96.30	#	#
E12	Almeria	37.26	51.00	29.60	29.60
E13	Algeciras	57.19	96.30	#	#
E14	Huelva	48.20	96.30	41.63	44.30
E15	La Mancha	32.33	51.00	29.60	29.60
E16	Santander	53.35	57.50	#	#

Note: # indicates that there are no carbon capture operations conducted at that industrial cluster under the scenario "Indus_only" (see the discussion in Section 2).

Table 7. The break-even price for CCS adoption $p^*_{CO_2}$ (€/tCO$_2$)

	Scenario "All"		Scenario "Indus_only"	
	χ_i Quantity-weighted (a)	χ_i Marginal (b)	χ_i Quantity-weighted (a)	χ_i Marginal (b)
North	89.01	114.25	82.62	82.62
difference		*+28.4%*		*+0.0%*
Central	39.17	57.84	36.54	36.54
difference		*+47.7%*		*+0.0%*
South	68.12	107.23	53.46	56.13
difference		*+57.4%*		*+4.99%*

Note: (a) These results were obtained using the linear program LP1 and the unit capture costs defined using equation **Erreur ! Source du renvoi introuvable.**. (b) These results were obtained using the linear program LP1 and the unit capture costs defined using equation **Erreur ! Source du renvoi introuvable.**.

Table 8. The simple cost metrics derived from accounting reasoning (€/tCO_2)

	Scenario "All"		Scenario "Indus_only"	
	Average cost (a)	Highest capture cost + average pipeline and storage cost (b)	Average cost (a)	Highest capture cost + average pipeline and storage cost (b)
North	56.60	107.30	48.50	68.06
Difference with $p^*_{CO_2}$	*-36.4%*	*-6.1%*	*-41.3%*	*-17.6%*
Central	39.17	57.84	36.54	36.54
Difference with $p^*_{CO_2}$	*0.0%*	*0.0%*	*0.0%*	*0.0%*
South	57.07	105.68	48.67	56.11
Difference with $p^*_{CO_2}$	*-16.2%*	*-1.4%*	*-9.0%*	*0.0%*

Note: (a) These results were obtained using the formula $\left[\sum_{i\in N}\sum_{j} Q_{ij}\chi_{ij} + C^*(N)\right] / \sum_{i\in N} Q_i$. (b) These results were obtained using the formula $\text{Max}_{ij}\chi_{ij} + C^*(N) / \sum_{i\in N} Q_i$.

Table A.1. Correspondence between our industrial clusters and the sources of CO_2 used in the COMET project

Cluster Label	Cluster name	Region	Correspondence with the sources of CO_2 used in the COMET project
E1	A Coruña	Galicia	C03, C17
E2	Oviedo-Gijón	Asturias	C01, C02
E3	Leon	Castilla-León	C04, C18
E4	Burgos	Castilla-León	C49, C12
E5	Bilbao	Euskadi	C24
E6	Pamplona	Navarra	C23
E7	Barcelona	Catalunya	C11
E8	Tarragona	Catalunya	C27
E9	Zaragoza	Aragon	C45, C46, C38, C36
E10	Valencia	Valencia	C30
E11	Cartagena	Murcia	C09
E12	Almeria	Andalucía	C34
E13	Algeciras	Andalucía	C22
E14	Huelva	Andalucía	C30
E15	La Mancha	Castilla-La Mancha	C05
E16	Santander	Cantabria	C31

Table A.2. The intersection nodes

Node	Name	Region	Node	Name	Region
R1	Miranda de Ebro	Castilla y Leon	**R8**	Osorno	Castilla y Leon
R2	Alfaro	La Rioja	**R9**	Córdoba	Andalucía
R3	Torrente de Cinca	Aragon	**R10**	Antequera	Andalucía
R4	Vinaròs	Valencia	**R11**	Guadix	Andalucía
R5	Murcia	Murcia	**R12**	Vera	Andalucía
R6	Granada	Andalucía	**R13**	Puerto Lumbreras	Murcia
R7	Seville	Andalucía			

Table A.3. The candidate pipelines

Pipeline	Origin	Destination	Distance (km)	Average terrain cost factor τ	Pipeline	Origin	Destination	Distance (km)	Average terrain cost factor τ
P1	E1	E2	286.0	1.34	**P26**	S3	R3	79.4	1.18
P2	E2	E16	194.0	1.32	**P27**	S3	R4	127.0	1.19
P3	E16	E5	99.7	1.12	**P28**	E10	S4	199.0	1.17
P4	E16	S8	75.0	1.44	**P29**	E15	S5	270.0	1.08
P5	S8	R8	84.0	1.21	**P30**	S5	E10	115.0	1.08
P6	E5	R1	82.2	1.20	**P31**	S5	R5	146.0	1.05
P7	R1	E4	86.0	1.09	**P32**	E11	R5	49.5	1.01
P8	E4	R8	67.0	1.03	**P33**	R5	S6	84.0	1.03
P9	R8	E3	120.0	1.02	**P34**	R6	S7	140.0	1.35
P10	E2	E3	125.0	1.35	**P35**	E14	R7	83.0	1.04
P11	E4	S1	84.6	1.03	**P36**	E13	R7	183.0	1.05
P12	S1	E15	221.0	1.04	**P37**	R7	R9	141.0	1.06
P13	E15	S4	127.0	1.07	**P38**	R9	S7	147.0	1.11
P14	E15	S7	251.0	1.09	**P39**	R6	R10	102.0	1.26
P15	R1	S2	65.8	1.15	**P40**	R10	E13	183.0	1.11
P16	E6	S2	85.1	1.09	**P41**	R7	R10	160.0	1.07
P17	E6	R2	86.4	1.10	**P42**	R9	R10	115.0	1.13
P18	S2	R2	71.7	1.02	**P43**	R11	R6	54.0	1.35
P19	R2	E9	104.0	1.02	**P44**	E12	R11	112.0	1.24
P20	E7	E8	99.0	1.20	**P45**	E12	R12	87.0	1.09
P21	E8	R3	122.0	1.18	**P46**	R12	E11	113.0	1.06
P22	R3	E9	121.0	1.16	**P47**	R5	R13	89.0	1.04
P23	E8	R4	115.0	1.08	**P48**	R13	R12	47.0	1.15
P24	R4	E10	151.0	1.50	**P49**	R13	R11	143.0	1.18
P25	E9	S3	105.0	1.03	**P26**	S3	R3	79.4	1.18

Figure 1. The geography of the emission clusters and the candidate pipelines and storage sites

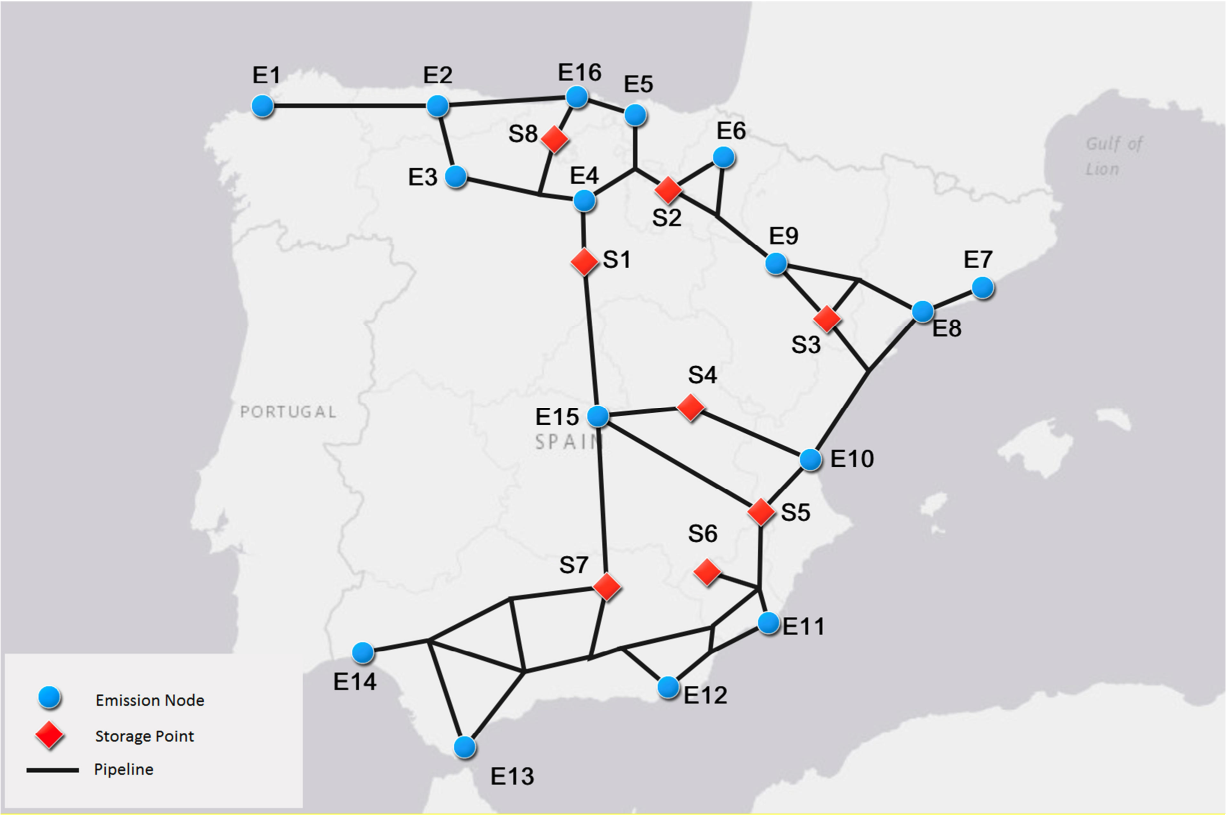
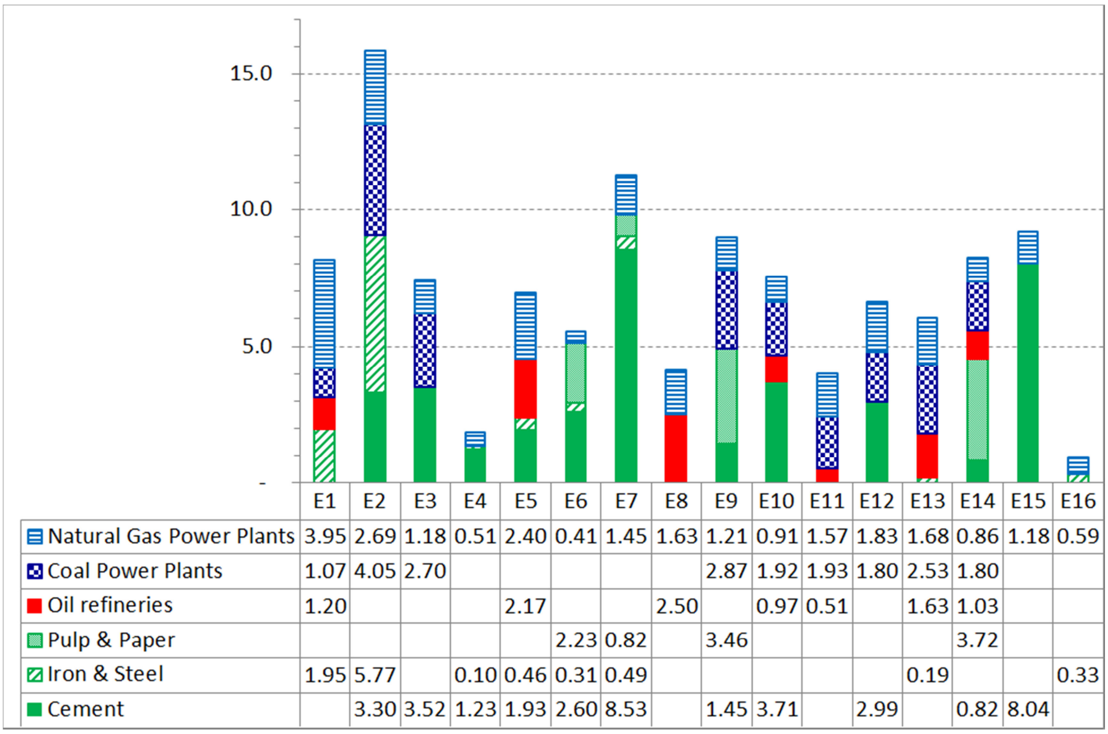


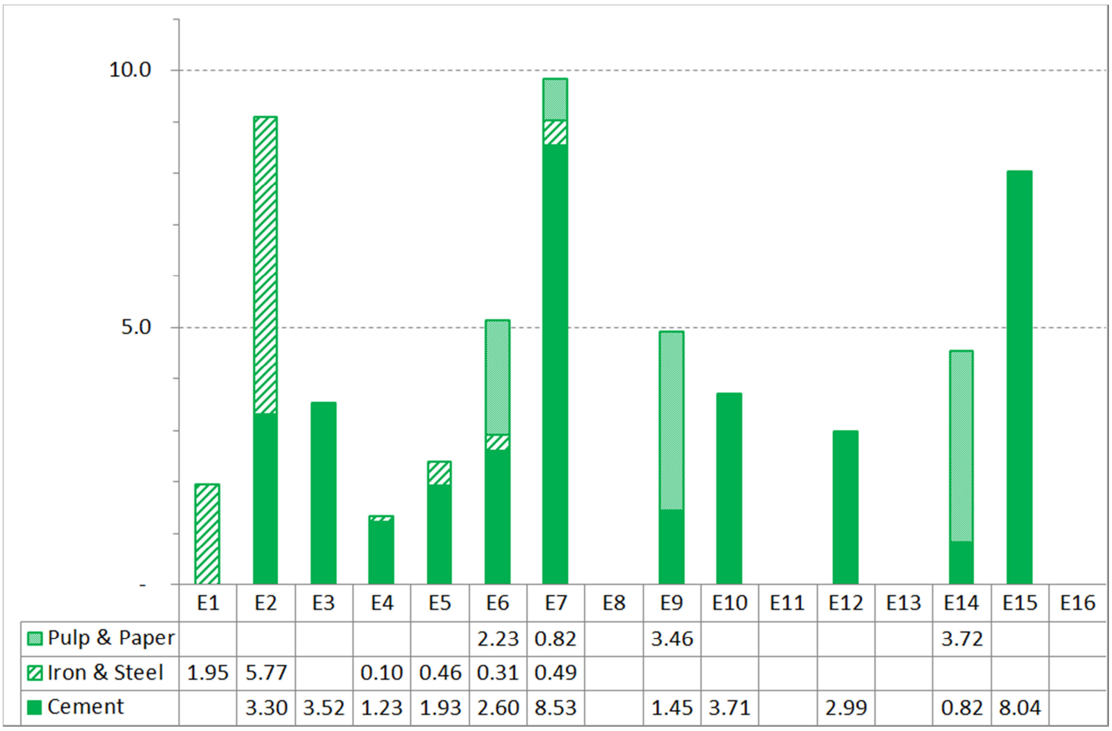
Figure 2. The capture potentials Q_{ij} at each cluster under each scenario (in MtCO$_2$/year)

(a) Scenario “*All*”



	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16
▤ Natural Gas Power Plants	3.95	2.69	1.18	0.51	2.40	0.41	1.45	1.63	1.21	0.91	1.57	1.83	1.68	0.86	1.18	0.59
▩ Coal Power Plants	1.07	4.05	2.70						2.87	1.92	1.93	1.80	2.53	1.80		
🟥 Oil refineries	1.20				2.17			2.50		0.97	0.51		1.63	1.03		
▦ Pulp & Paper						2.23	0.82		3.46					3.72		
▨ Iron & Steel	1.95	5.77		0.10	0.46	0.31	0.49						0.19			0.33
🟩 Cement		3.30	3.52	1.23	1.93	2.60	8.53		1.45	3.71		2.99		0.82	8.04	

(b) Scenario “*Indus_only*”

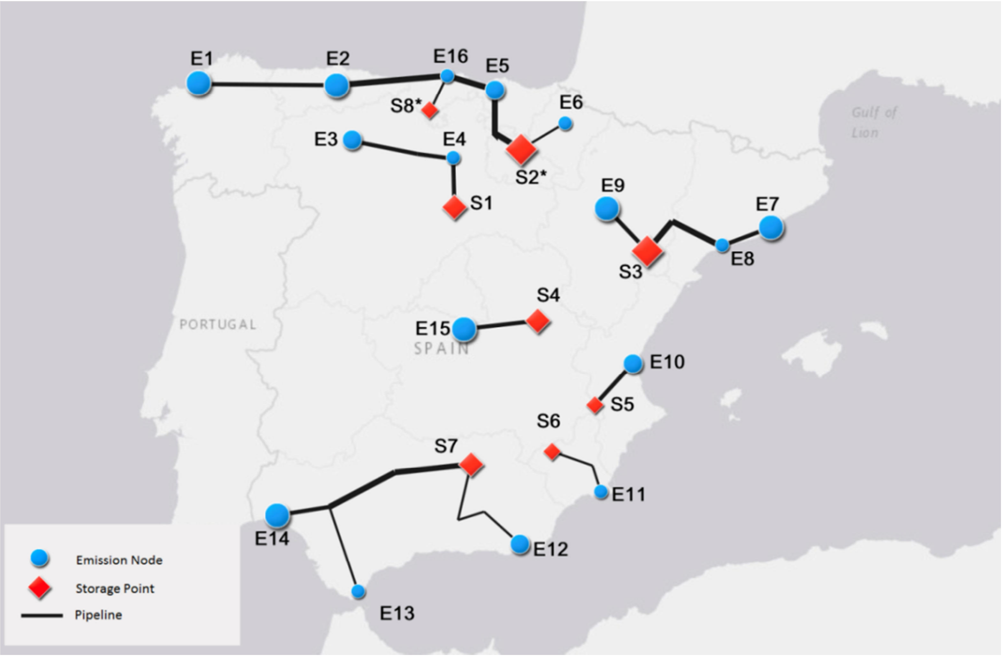


	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16
▦ Pulp & Paper						2.23	0.82		3.46					3.72		
▨ Iron & Steel	1.95	5.77		0.10	0.46	0.31	0.49									
🟩 Cement		3.30	3.52	1.23	1.93	2.60	8.53		1.45	3.71		2.99		0.82	8.04	

Source: Simulation results of the TIMES-COMET model under the central scenario.

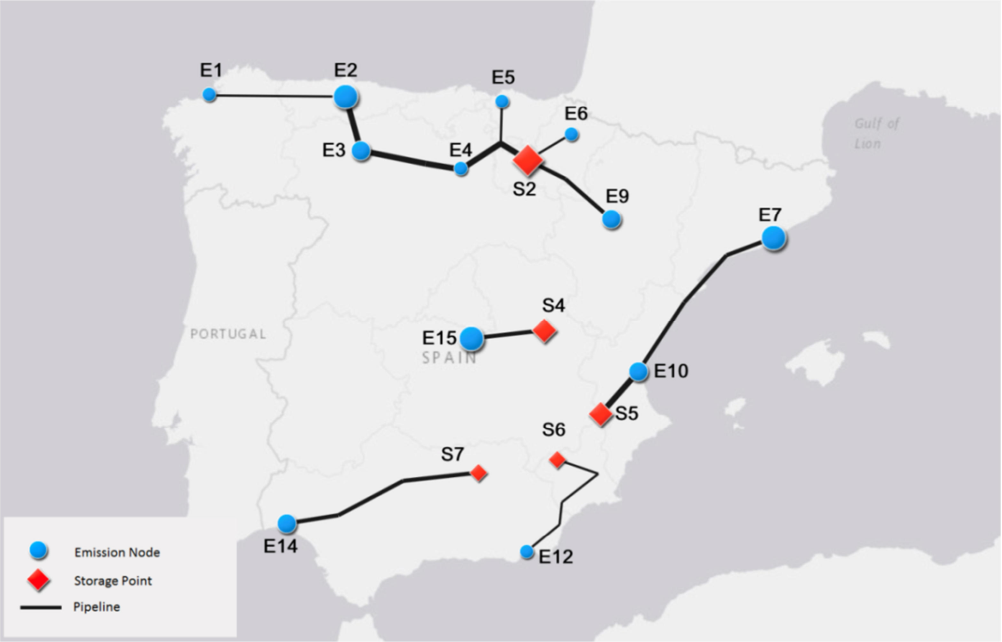
Figure 3. CO_2 pipeline and storage deployment in Spain

(a) Scenario "*All*"



Total volume of CO_2 captured and stored:	112.7 $MtCO_2$/year
Total length of the pipeline system:	2,800 km
Total annual equivalent cost:	€1,160.8 million
Total annual equivalent pipeline cost:	*€694.7 million (59.8% of the total)*
Total annual equivalent storage cost:	*€466.1 million (40.2% of the total)*

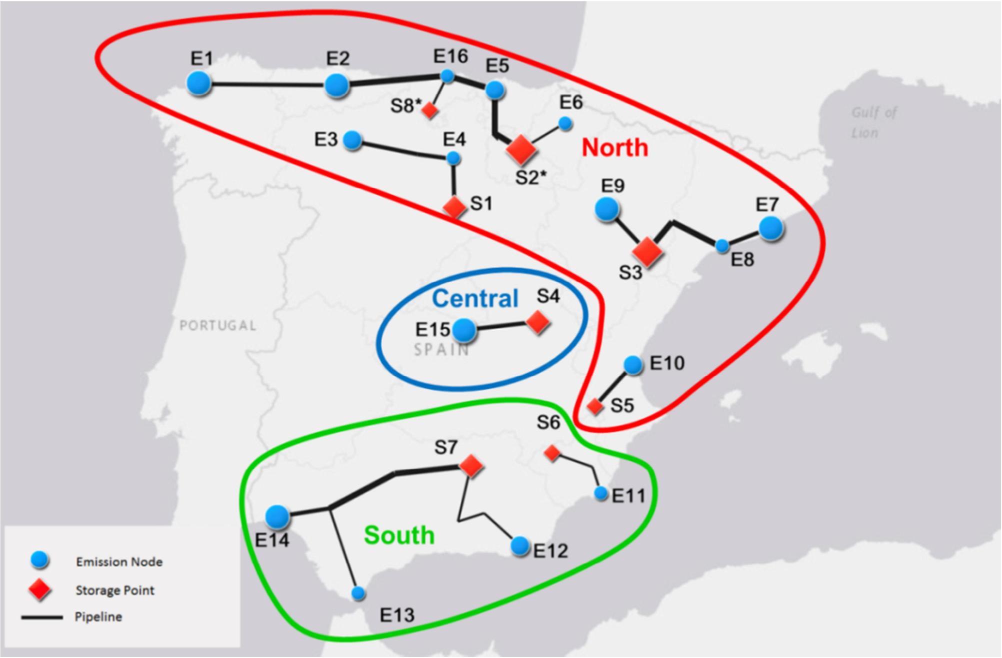
(b) Scenario "*Indus_only*"



Total volume of CO_2 captured and stored:	55.2 $MtCO_2$/year
Total length of the pipeline system:	2,378 km
Total annual equivalent cost:	€586.6 million
Total annual equivalent pipeline cost:	*€418.3 million (71.3% of the total)*
Total annual equivalent storage cost:	*€168.3 million (28.7% of the total)*

Figure 4. An illustration of the three independent subsystems

(a) Scenario “*All*”



(b) Scenario “*Indus_only*”