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**Region specific challenges of a CO₂ pipeline infrastructure in the West
Mediterranean area
Model results versus stakeholder views**

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Abstract

This paper presents results of potential CCS infrastructures in the West Mediterranean region including trajectories for CO₂ pipelines. The preliminary results are generated with a combination of geographical (GIS) and partial equilibrium optimization modelling (MARKAL/TIMES-COMET). Furthermore, as a result of active stakeholder involvement in the research project, the CCS infrastructures were critically reviewed and obtained insights were used to improve the models and their input parameters. Stakeholders' feedback regarding difficulty in crossing hard rock terrains and the reasonability of trying to replicate the existing natural gas network, had a large impact on the resulting CCS infrastructure.

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1. Introduction

Carbon dioxide Capture, Transport, and Storage (CCS) is a CO₂ abatement option that can contribute around 20% to the global CO₂ emission reduction which is required in 2050 to stay below a 2°C average global temperature increase [1]. While CO₂ capture technology can be developed at an international level,

the development of a CO₂ transport and storage infrastructure asks for insights into specific regional and local circumstances. In the EU co-funded COMET project, these insights are generated for the West Mediterranean area consisting of Spain, Portugal, and Morocco. Due to its peripheral location, this region will have difficulties in connecting to other CCS networks in Europe or Africa. In these countries, which were responsible for emissions from stationary sources of 170 Mt CO₂-equivalent in 2009, the identification and assessment of cost effective CO₂ transport and storage infrastructure help to achieve timely decisions on the deployment of CCS. On the technical side this asks for the determination of the role of CCS in a mitigation portfolio, the identification of CO₂ sources and CO₂ storage locations, and the selection of transport routes. However, this technical analysis must be balanced by engaging stakeholders able to provide insights and experience about the regional specific issues. This dual approach, technical analysis and stakeholder engagement, is the basis of COMET. This paper, specifically, addresses the selection of transport routes based on geographical and energy system analysis, and the feasibility of actually realising CO₂ transport over these routes taking into account region specific challenges through interaction with stakeholders.

2. Methodology

The methodology to select viable CO₂ transport routes in the West Mediterranean region consisted of 5 main steps: i) creation of a model in a Geographical Information System (GIS) based on factors constraining pipeline building in the region and specific relative costs assessed through stakeholder questionnaires; ii) calculation of potential CO₂ transport routes between source and sink clusters based on least-cost algorithms in the GIS model; iii) identification of cost-effective trajectories with the help of the TIMES-COMET model, an energy system model of the study region; iv) consultation of stakeholders in workshops in Morocco, Portugal, and Spain; v) update of input data and scenario input parameters based on the stakeholder consultations, and repetition of steps i-iii resulting in the final CO₂ transport trajectories. Interaction with stakeholders occurs in steps ii) and iv) and proved essential for the results obtained in v).

As part of step i, the geographical, environmental, land use, and infrastructure constraints for building a pipeline network were implemented into a GIS, which already included the source and sink inventory. Next a cost model was defined based on a linear modelling approach as also applied in [2] and [3] in which the GIS was used to account for geographic cost deviations. On the 300 m cell-size resolution of the GIS, a cost factor grid was constructed, resorting to **terrain factors** that represent relative cost variation from the standard construction cost, taking into account four variables: i) **land use**; ii) **terrain slope**; iii) **crossing** of existing infrastructures and, iv) the availability of **corridors** where natural gas or oil pipelines already exist. The pipeline investment cost is computed by integrating the costs in all the cells along the pipeline trajectory as follows:

$$I = B_c * D * \sum \{ F_c * F_s * [F_{lu} * (1 - 0.1N) + 0.1N * F_{ci}] * L \} \quad (1)$$

where I are the *total* pipeline investment cost (€₂₀₁₀); B_c is the standardized cost factor (€₂₀₁₀/m²); L is pipeline length; D is pipeline diameter and F_{ci} , F_s , F_{lu} and F_c are the terrain factors for crossings, slope, land use, and corridors, respectively. N is the number of infrastructures being crossed in each cell and, to avoid overestimation of the costs, it was assumed that each of the infrastructures could occupy 10% of the cell, the remaining being accounted for by the land use factors.

Because the aim was to find the most viable network, including optimization of investment costs, the whole modeling exercise rests on the definition of the variables in equation 1, namely the terrain factors and the standardized cost, as the length, number of crossings and diameter of pipeline are an outcome of the modeling procedure. The values of the terrain factors and standardized cost factors were based on a literature review and on consultations with the stakeholders who are responsible for managing or building oil and natural gas pipelines in the three countries.

As part of step ii, CO₂ sources (with emissions > 0.1 Mt/year) and sinks were grouped into source and sink clusters, taking into account the distance between individual sources and sinks. Also other criteria were applied such as geographical and infrastructure barriers in the case of sources, and continuity of geological basins and offshore/onshore setting in the case of sinks. Thus, possible CO₂ transport trajectories could be identified allowing for economies of scale to transport CO₂ from several sources through trunk lines to various sinks. Based on the cost grid and cluster hubs locations, least cost trajectories were identified using the least cost routing function in GIS. Not only were trajectories sought between source and sink clusters, but also between sink and sink clusters, and source and source clusters. Thus, it would, for example, be possible to select routes to transport CO₂ from a source cluster via other clusters to a sink cluster. This strategy allows not only to find the minimal investment costs for the trunk line originating from a single cluster, but also to optimize the cost of the entire transport network in the target region.

In step iii, cost-effective CO₂ trajectories were identified with the help of the TIMES-COMET model, which is a bottom-up technical economic equilibrium model hard-linking the national energy system models of Morocco, Portugal and Spain [4] and the CCS infrastructure model of the region [5, 6]. More than 3000 trajectories were used as input for the model in order to take care that the model had several options to store CO₂ from any source in any sink by combining different trajectories.

Step iv comprised of stakeholder consultation. Three national workshops were organized in Morocco, Portugal, and Spain with the main objective to get detailed feedback from national stakeholders. The stakeholders who participated, represented ministries (Environment, Economy and Marine Affairs), transmission system operators, power plant operators, cement industries, mining, oil and gas companies, environmental NGOs, and universities. Based on the preliminary results of the TIMES-COMET model, the stakeholders advised on the data gathered, scenarios, energy system modeling results, and CO₂ transport networks.

In step v, all comments from the stakeholders were evaluated whether they could be implemented in the GIS least cost-routing or the TIMES-COMET energy model activities. The necessary adaptations were made, and new least cost trajectories were calculated and TIMES-COMET was re-run to select specific CO₂ trajectories (where, when, how much CO₂ transported). Multiple scenarios were studied among others distinguished by the level of CO₂ emission reduction, and the option to cross boundaries or not. The resulting development of CO₂ infrastructure could then be further analysed and visualised in maps.

3. Results

3.1. GIS input data (step i) and calculation of least cost routing trajectories (step ii)

Table 1 gives an overview of the literature values, experts' opinions and COMET values for the standardized cost factor and terrain factors. Note that the range of values found in literature was large for

the standardized cost factor and several terrain factors on land use (urban and associated areas, protected areas) and water body crossings. However, due to feedback from the Spanish natural gas owner and operator Enagás (which collaborates with the Spanish utility company Endesa, partner of the COMET project), and the Portuguese utility companies REN (Redes Energéticas Nacionais) and Galp Energia, we were able to find more solid values for these cost factors.

Table 1. Overview of cost terrain factors as found in literature, indicated by national stakeholders and used for the COMET modelling exercise (blue column).

		International Literature		Stakeholder questionnaires	COMET
Constant cost factor on-shore pipelines	€2010/(m*m)	1471 ^{1,2} /1989 ²		1400 ³ / 1200 ⁴	1357
Operation & Maintenance	€2010/(m*m) / y			24/time dependent	24
Terrain Factor					
Land use (F _{lu})	Unpopulated	1		1	1
	Urban and associated areas	1.4/2.0/15		1.6/2.0	1.8
	Protected areas	10/30		1.4/no way to cross	10
	Cultivated land			1.1	1.1
	Forest			1.5/1.05	1.3
	Bare areas	1.1/1.3		1.1	1.1
	Water bodies	1.8/3/10		4/horizontal drilling: 1 M€/km; soft land: 2.5 M€/km hard rock	4
	Regularly flooded				1.2
Crossings(F _{ci})	Roads	3		3/3000€/m width	3
	Railways			3/3000€/m width	3
	High speed railways				3
Corridors (F _c)	Offshore (dev. from exist. pipelines)	1.0	14	3/>1	3
	Offshore (fol. exist. pipelines)	0.9		NA/>1	2.7 ⁵
	Onshore (fol. exist. pipelines)	1.0		NA/>1	0.9
	Onshore (dev. from exist. pipelines)	1.5			1.0
Slope (F _s)	<10%	1			1
	10-20%	1.1/1.3		1.1	1.1
	20-30%	1.3/1.4		1.2	1.2
	30-70%			Not asked in questionnaires; categories were included after stakeholder workshops	3.0
	>70%				9

¹ Original value was given in EUR2007. This value was corrected for inflation and industrial price changes using the European Capital Cost Index. ² These costs are based on natural gas pipelines. ³ Including all CAPEX components: Engineering, Materials, Construction, Start-up, Permits, Land cost, Rights of way. ⁴ Plus 1,200,000 € per one meter diameter block valve station. Block valve station spacing: 10 km suburban, 20 km country areas, start and end of pipeline. ⁵ Terrain factors for offshore pipelines deviating and following existing pipelines as indicated by Broek et al. [2] were 1.0 and 0.9, respectively. A similar ratio was applied for the higher terrain factors used for Portugal, Spain and Morocco, thus resulting in a terrain factor of 2.7 for off-shore pipelines following existing pipelines.

For the COMET model, it was decided to take the average of the values provided by Endesa, REN, and Galp. An exception was made for the terrain factors ‘regularly flooded’, for which we choose a new value, and (the crossing of) ‘high speed railways’, for which the stakeholders did not give any feedback; for the latter parameter a literature value was used. Another exception was made for the terrain factor ‘protected areas’. As crossing protected areas was considered to be undesirable from an environmental, social acceptance, and legal point of view, an artificially high terrain factor (10) was used to let the model

select alternative routes. Finally, as Portuguese stakeholders indicated that the investment costs of offshore pipelines are about three times higher than for onshore pipelines, mainly due to the deep and local ocean conditions, we decided to assign a terrain factor of 3 for offshore pipelines. Given the large seabed depths in the Mediterranean Sea, we assumed that these terrain factors are also representative for the Spanish and Moroccan case.

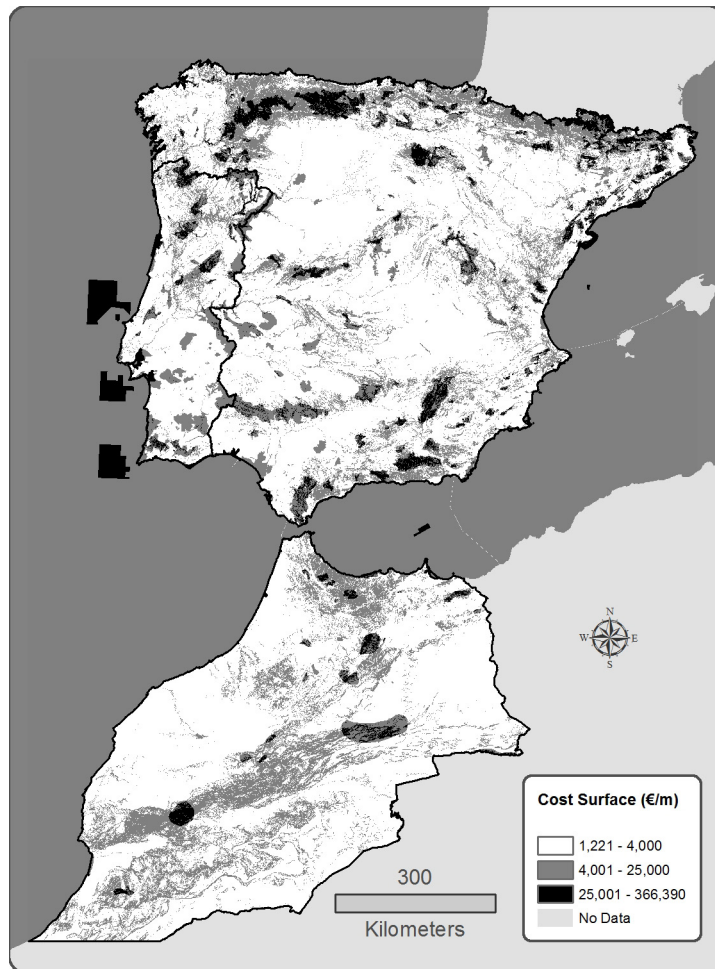


Figure 1. Cost surface map of the West Mediterranean region based on terrain factors identified in the COMET project.

Having defined the cost factors, implementation of equation 1 through map algebra with the multiple themes in the GIS model, resulted in a **cost surface map** representing the investment costs in each cell (Fig. 1) and immediately indicating the most costly areas for any pipeline to cross. Minimizing the sum of costs in each cell between source and sink clusters results in the least cost network.

In step ii, all sources and sinks were grouped into clusters. Application of the cluster criteria to the 285 stationary sources resulted in the definition of 8 source clusters in Portugal, a similar number in Morocco, and 39 in Spain. Furthermore, 23 sources were left isolated, not being included in any cluster. The 163 individual sinks were clustered in 29 clusters, of which 3 are transboundary clusters, 4 clusters are located

in Portugal, 2 clusters in Morocco, and the remaining 20 in Spain. Fourteen sinks were kept isolated whenever they were too distant from other potential storage sites or when the nearest storage sites are in a different onshore/offshore setting.

The least cost routing exercise with GIS revealed the following aspects. Apart from distance, the main factors influencing pipeline costs appeared to be the large number of crossings in Portugal and Spain, and to a lesser degree, in Morocco. High terrain factors imposed to environmental protected areas, usually translated in longer paths, with pipelines deviating around those areas. Topography in Northern Spain played an important role in the pipeline costs and routes, unlike for Portugal and Morocco, where most sources and sinks are located close to the coast, without major topographical barriers. In spite of the highest costs imposed to steeper terrains, some routes in the three countries crossed mountainous areas, instead of taking longer paths around the mountains. Notice that the terrain factors imposed in the GIS do not take into account the costs associated to the need of including booster stations in steeper terrains.

The modeling strategy implemented in the GIS ignores the amount of CO₂ produced in the source clusters, the available storage capacity in the sink clusters, and the amount of CO₂ being transported in the pipelines (in fact costs were obtained per meter diameter). Thus, no source-sink matching procedure was conducted at this stage, as this was part of the route selection exercise by the TIMES-COMET model.

3.2. Selection of cost-effective trajectories (step iii) and stakeholder consultation (step iv)

With the source and sink matching procedure defined and CO₂ flow between sources completed, the GIS was again used to generate the actual pipeline routes representing the CO₂ flows retrieved by TIMES COMET. These CO₂ flow and pipeline routes maps were essential for consultation with stakeholders in the next stage.

During the workshops stakeholders were invited to evaluate whether the routings calculated with least cost routing and selected by TIMES-COMET, are feasible to construct. The CCS infrastructures were critically reviewed by the stakeholders, and insights were obtained on how the models and their input parameters can be improved to generate valid outcomes. The issues which were addressed by the stakeholders during the workshops and have led to a change in the least cost routing exercise and/or the TIMES COMET model are presented in table 2. Where lack or outdated data was identified (for example, for existing pipeline locations of which information is sensible and difficult to obtain with the accuracy desired) efforts were conducted to collect or update that data. Two stakeholder comments proved particularly important for the re-calculation of the transport networks in step v: difficulty in crossing hard rock terrains and the reasonability of trying to replicate the existing natural gas network.

Table 2. Overview of stakeholder inputs.

Morocco
CCS was not considered to be a likely option in the energy system for Moroccan objectives, but could be implemented in Morocco as part of a global/ European CO ₂ emission reduction strategy.
The total CO ₂ storage capacity seems limited in comparison with the Moroccan yearly emissions. The selected sedimentary basins for CO ₂ storage extend along the Atlantic coastline from Tanger to Agadir, which hosts most of CO ₂ emission sources (power plants, the refinery of Casablanca, cement plants, chemical plants). In the Gharb region, it could be possible to integrate small storage capacities to generate a more acceptable total capacity. In order to increase Moroccan CO ₂ storage capacity estimates, it is important to have an estimate of the Atlantic offshore CO ₂ storage capacity.
Location of future new industrial activities and emissions would be around Casablanca (two clusters: Jorf Lasfar and Safi), Tanger, North East. In Marrakech, no new industrial activities are expected. The new coal-fired power plants will be located around Safi.

2 new cement factories (production capacity 1.6 million tons): the 1st, already operating at 100% since 2011, is located in the town of Ben Ahmed (70 km from Casablanca), the 2nd is located near Beni Mellal (basically operating in 2012).
Too many land owners is a very big problem to build a pipeline because you have to pay each of them. Land ownership is often complex and mixture of properties exist partly based on ancestral systems. Also, population may resist for other reasons (e.g. security reasons).
The geological interest area that will be protected in a coming law should be taken into account.
Pipeline across the Rif is not plausible, on lesser degree the one from Tanger across some mounts and the one from Agadir to Essaouira.
South of Agadir, there is a protected area. Transport pipelines should not cross this.
The presented connection of JLEC power plant (5,9 Mt of CO ₂ /year) is not realistic
A pipeline should cross as few administrative areas (provinces) as possible because each of them will impose a tax. It may be worthwhile to find pipeline trajectories which cross as few administrative areas as possible.
Portugal
The outcome of the non-existence of any future coal power plant without CCS is probable.
The location of some of the existing pipelines in the GIS map is incorrect; REN will provide a geo-referenced digital file of existing pipelines
Despite the uncertainty in costs, CCS was recognized as an opportunity for the industry, mainly for cement industry, since power sector will rely to a large extent on competitive renewable energy sources. However, new cement capacity would not be always located at existing locations, because the raw materials from some quarries may have ended before 2050.
CO ₂ pipelines crossing surface geological formations like hard rock should not be considered, or should be taken very carefully with further research on transport costs. Past experiences with NG pipelines crossing hard rock have shown very high costs.
Additional cost for transboundary pipelines should be taken into account, following the actual regime for natural gas transboundary pipelines that pay an additional fee to cross the border or run alternative scenarios without transboundary CO ₂ pipelines.
Synergies could be achieved by using existing routes from natural gas or water transportation, highways, or railways, and by ROW sharing.
CO ₂ construction projects could make use of the recent experiences with natural gas networks and oil pipelines covering the whole project life cycle of planning, construction, and operation. It is also important to guarantee a public service concession for the transport and storage of CO ₂ (similar to natural gas, water and electricity).
There is a lack of experience with operating and maintenance of CO ₂ transportation and with offshore pipelines. Difficult terrains in mountainous areas would increase costs and give rise to technical difficulties.
Attention should be paid to scheduling the pipeline network starting operation and CO ₂ capture technologies availability in industries and power plants. It is also very important that the involved stakeholders understand the economic justification of a CCS infrastructure.
Spain
The characteristics and potentials of the sinks need to be investigated before committing too much to CCS.
In Spain orography raises the cost of CO ₂ transport and is an important issue to take into account when planning a CO ₂ pipeline network.
About sinks, the main ones in Spain were shown in the results of the project and, although there is little geophysical information on those sinks, from the information gathered in other projects they seem suitable, and among them, specially the Duero basin one.
It is reasonable to let the CO ₂ transport network be located in parallel with the existing gas transport network.
There is also a concern on how the relationship among the different regions in Spain (each with its own autonomous government) will be regarding the CO ₂ transport network.
The near transposition of Directive 2010/75/EU, of 24 November 2010, on industrial emissions (integrated pollution prevention and control), into national laws would have an important influence in the electricity production from the coal power plants in the short term. This transposition, to be in force in January 2013, will bind the existing coal power plants to reduce their SO ₂ and NO _x .

emissions. Meeting the NO_x emissions reductions will force all the plants to incorporate new techniques with the corresponding huge investment, but given the age of these old plants and the economic situation, this may result in shutting down in the very next future.

The assumption of building new coal-fired power plants in the same clusters where there are existing coal-fired power plants makes sense since in Spain all the coal plants are located close to the resource. All those plants were built at short distances from the coal mines and import ports, in these clusters there is already a coal exploitation infrastructure and an economy based on this activity.

3.3. Least cost routing and energy modeling revisited with input from stakeholders (step v)

Stakeholders in all three countries had identified that some of the pipelines cross high ground, where excavation in hard-rock would make it unfeasible/uneconomic to install pipelines. The main cost associated to laying pipelines in hard rock terrains is the cost of excavating. Including geological information in the GIS model on surface geology would, however, not solve the problem, because these data do not necessarily reflect the hard-rock or soft-rock nature to the depth of excavation for installing small diameter pipelines, say down to 1-2 m depth. It was decided to use ground slopes as a proxy for the hardness of the underground (soft or hard rock) by assigning higher cost terrain factors to the ground slopes, the higher costs for excavating are covered. Similar approaches are used in other scientific fields, such as geotechnical engineering and soil mechanics (e.g. [7]). We observed from several data sources like the Spanish building costs database [8] that the costs factors of excavating in soils to excavating in soft rock and hard rock, vary from 2.5 to 9.2, if one excludes the use of explosives. Given the slope range indicated before, we decided to use a cost terrain factor of 3.0 for slopes ranging from 30-70% and 9 for slopes steeper than 70% (assuming excavation in hard rock).

Other comments of the stakeholders were taken into account by adapting the scenario input parameters of the TIMES-COMET model. The advice of the stakeholders that CO₂ pipelines seem more likely if they follow gas pipelines, was implemented by only allowing these pipelines in the solution in a conservative CCS scenario. This scenario was also run without the option of cross-boundary transport to take into account potential high tariffs for these crossings. Nevertheless, other scenarios were built with the possibility of cross-boundary transport and free CO₂ routes for analysis of alternative cases. Specific comments about potential locations of future CO₂ sources were taken into account by allowing these CO₂ sources in specified regions or not. The GIS model was rerun to update the cost matrix and TIMES-COMET model updated the source sink matching and selection of trajectories. Figure 2 shows the preliminary results of the pipeline network in 2030 for the Conservative CCS scenario.

4. Conclusions

The paper presents the preliminary results of CCS infrastructures which were generated by a combination of a geographical (GIS) and a partial equilibrium optimization model (TIMES-COMET). Furthermore, as a result of the active stakeholders' involvement in the research project, the CCS infrastructures were critically reviewed and refined, and insights were obtained to improve the models and their input parameters. Stakeholders' feedback regarding difficulty in crossing hard rock terrains and the reasonability of trying to replicate the existing natural gas network, had a large impact on the resulting CCS infrastructure generated by GIS and the TIMES COMET model.

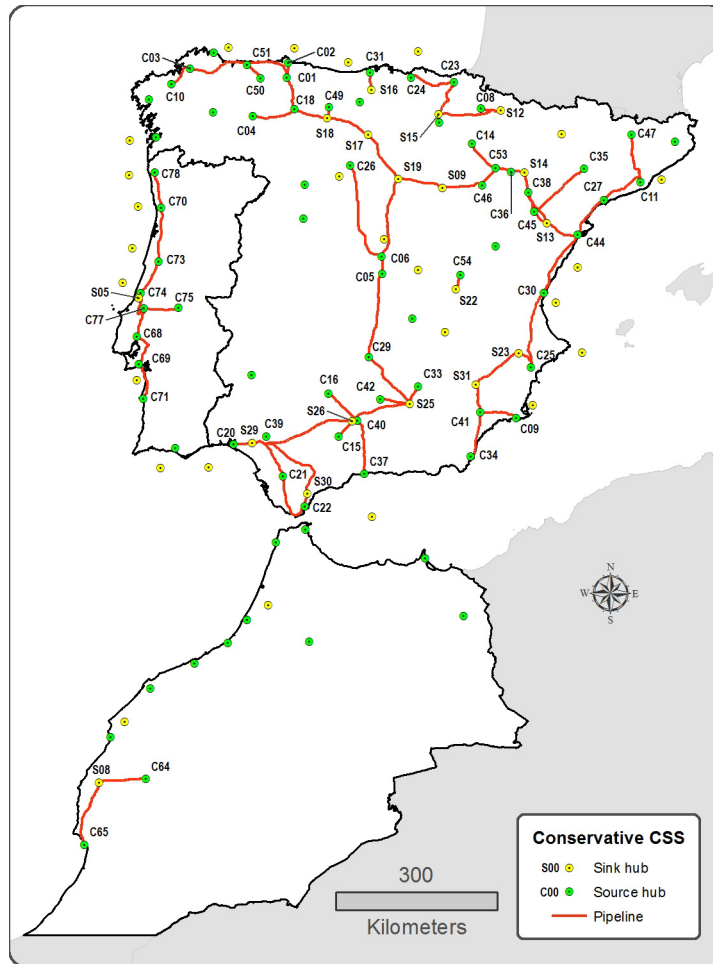


Figure 2. Preliminary results of possible CO₂ infrastructure in 2030 in a scenario with high demand, a mitigation goal of 40% reduction in 2050 compared to year 1990, the requirement that pipelines follow preferably existing gas pipelines, and without cross-boundary transport.

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