

Method for identifying drivers, barriers and synergies related to the deployment of a CO₂ pipeline network

A case study for the Iberian Peninsula and Morocco



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ABSTRACT

This paper provides a method to identify drivers, barriers and synergies (DBS) related to the deployment of a CO₂ pipeline network. The method was demonstrated for the West Mediterranean region (WMR) (i.e. Spain, Portugal and Morocco). The method comprises a literature review, analysis of embedded pipeline trajectories, interviews with experts, and workshops with stakeholders. Subsequently, the collected information was used to identify route specific DBS in several CO₂ pipeline network deployment scenarios that were modeled for the WMR. Most identified DBS apply to CO₂ pipeline transport in general. The barriers (e.g. technical knowledge gaps, outstanding legislative issues, lack of financial incentive) can in principle be tackled to make the design, construction and operation of a CO₂ pipeline network possible, but could sometimes lead to somewhat higher costs. Furthermore, there are also facilitating processes (e.g. experience with CO₂ pipeline transport for EOR). Cost benefits due to pipeline oversizing were identified as a route specific driver, whereas crossings of mountains, water and nature areas are route specific barriers. Installing CO₂ pipelines along natural gas pipelines could be either a route specific synergy or barrier, depending on site conditions. Finally, several key measures were proposed to enable CO₂ pipeline networks in the future.

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1. Introduction

CO₂ capture and storage (CCS) can play a key role in a portfolio of greenhouse gas emission (GHG) reduction options needed to achieve the stabilization target of 450 ppm(v) CO₂-equivalent (IEA, 2012). A key condition to the worldwide proliferation of CCS is the development of large-scale transport networks, which will form

Abbreviations: CCS, carbon capture and storage; CFS, cross-frontier scenario; CS, conservative CCS scenario; DBS, drivers, barriers and synergies; EOR, enhanced oil recovery; ETS, emission trading scheme; FRS, free-routes scenario; GDP, gross domestic production; GHG, greenhouse gas; GIS, geographical information system; GTP, CO₂ pipeline transport in general; IEA, international energy agency; MOP, multiple oil products; PIG, pipeline inspection gauge; ppm(v), parts per million (by volume); PPP, public private partnership; ROW, right of way; SPT, specific CO₂ pipeline transport; t, metric tonne; WMR, West Mediterranean region.

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the essential link between the carbon capture and storage step. First estimations of the International Energy Agency (IEA, 2010) indicated that extensive worldwide pipeline networks of between 200,000 and 550,000 km would be required, depending on the configurations of the networks, to avoid approximately 8.2 GtCO₂ in 2050, which is around 19% of the necessary reduction worldwide (Knoope et al., 2013). The large-scale deployment of pipeline networks as envisioned by the IEA requires timely and stable action (GCCSI, 2012). Region-specific roadmaps are needed to deal successfully with all aspects of CO₂ network development, including measures to remove potential barriers related to pipeline technology, legislation, policy, economics, finance and organization, which could hamper the deployment of pipeline infrastructures (Element Energy Limited, 2010a; GCCSI, 2012). In addition, efforts should be made to exploit the existing experience and knowledge base accumulated with conventional pipeline transport and CCS demonstration projects, which could drive and expedite the development of CO₂ pipeline networks. A comprehensive overview of relevant

and important drivers, barriers and synergies (DBS) is, therefore, desirable to serve as input for region-specific roadmaps.

Several studies aimed to identify DBS related to CO₂ transport infrastructures. These studies are mainly based on literature reviews and desktop research (e.g. ICF International, 2009; Insight Economics, 2011; Wu and Ramírez, 2010). Some analyses also included interviews with stakeholders to gauge their views on various aspects of a potential CCS network (e.g. ICF International, 2009; Mikunda et al., 2011b), studies of pipeline trajectories transporting hydrocarbons or other substances to draw lessons from other pipeline industries¹ (NERA Economic Consulting, 2009a,b), or both (Chrysostomidis and Zakkour, 2008). Research carried out by Element Energy Limited (2010b,c) comprised workshops with groups of stakeholders, but excluded the analysis of analogue pipeline trajectories. Whereas some of these studies (e.g. Element Energy Limited, 2010b) covered multiple aspects (i.e. technology, legislation, policy, economics, finance and organization) of CO₂ pipeline networks, most studies (e.g. DECC, 2010; ICF International, 2009) focused on merely one or two aspects (i.e. technology and legislation). In addition, nearly all referenced studies originate from industry. To the authors' knowledge, a comprehensive and consistent, yet thorough method, including all the aforementioned data collection methods and covering all relevant aspects, to identify the DBS for a regional pipeline network is currently not available in the scientific literature.

The main objective of this paper is, therefore, to provide a method for the DBS related to the deployment of a regional CO₂ pipeline network. The DBS cover the aspects of technology, legislation/policy, economics/finance and organization. Although relevant, the aspect of public perception was excluded from the analysis as the topic was too broad for the scope of this study. In this paper, the West Mediterranean region (WMR) (i.e. Spain, Portugal and Morocco) was selected as a case study to demonstrate the method. Such an inventory has hitherto not been carried out for this region. In the COMET project, the potential role of CCS in the WMR as well as several possible CO₂ pipeline networks have been modelled (Gouveia et al., 2013; Kanudia et al., 2013, 2012a,b,c; Van den Broek et al., 2013b) (see Section 2). The results showed that CCS can play an important role in the WMR to achieve deep CO₂ emission reductions. Moreover, the WMR is a suitable region for CCS considering its large CO₂ storage capacity, mainly in the form of saline aquifers, but also oil and gas fields (Martínez and Carneiro, 2011). If CCS will take off on a large scale, the Iberian Peninsula (and Morocco) will likely form its own integrated CO₂ pipeline network with no connections to central and northwest Europe, due to the large distances involved and the mountain ranges in between (Mikunda et al., 2011b; Van den Broek et al., 2013a). Furthermore, the heterogeneity among the countries in terms of economic development and legal framework (EU vs. non-EU) could possibly result in the identification of drivers, barriers and synergies (DBS) that are currently still unknown. In addition to generic DBS, this paper aims to identify and assess specific DBS related to the CO₂ pipeline network configurations and deployment pathways modelled in the COMET project.

2. Methods

This section presents the method to identify the DBS related to the deployment of a CO₂ pipeline network (Section 2.1). The case study and data collection are discussed in Section 2.2.

2.1. Approach

Prior to this analysis, a model was designed to simulate CO₂ pipeline network deployment scenarios for the WMR (see Kanudia et al., 2013, 2012a,b,c; Van den Broek et al., 2013b). These deployment scenarios were used to identify the specific DBS, hereafter referred to as route specific DBS, related to the CO₂ pipeline networks across the WMR. Although this modeling step is not part of this paper, a short description of the model is given in Section 2.1.1 to create a better understanding of the simulated pipeline networks. Next, definitions are given for the DBS (Section 2.1.2). The scoring procedure, data collection and the procedure for the identification of the route specific DBS are described in Sections 2.1.3–2.1.5, respectively.

2.1.1. COMET model

The tailor-made COMET model was designed using a system analytical approach based on bottom-up techno-economic models generated by the MARKAL-TIMES software and geographical information system (GIS). The approach was chosen to integrate spatial, temporal, and techno-economic aspects to determine the role of CCS in the energy system and the development of the CCS infrastructure. Multiple scenarios were built, each with different assumptions on inter alia Gross Domestic Production (GDP) growth and concomitant CO₂ emissions. Based on these scenarios, several potential CO₂ pipeline networks were simulated. More information on the model can be found in Kanudia et al. 2013, 2012a,b,c).

2.1.2. Definitions

The DBS are categorized into four themes: technology, legislation/policy, economics/finance and organization. In this study, a *driver* is defined as a factor that enhances the design, construction and operation of CO₂ pipeline networks. A *synergy* is a situation in which benefits can be attained by combining two or more processes. A *barrier* is defined as a factor that impedes or delays the design, construction and operation of CO₂ pipeline networks. In this study, the terms driver, barrier and synergy can refer to present DBS (e.g. current low CO₂ price) or to (potential) DBS in the future (e.g. sub-optimal buildout of a large-scale CO₂ pipeline network). Table 1 presents examples of the DBS for each theme to clarify the concepts.

2.1.3. Scoring procedure

The data collection was divided into an international literature review and information collection at the national country level. The scoring procedure is shown schematically in Fig. 1. The DBS that were identified in international literature or in a particular country were indicated with a tick (✓). In case the DBS were *not* identified by a local stakeholder and/or project partner, but was after discussion with local stakeholders confirmed or expected to apply to this particular country as well, they were indicated with a plus (+). In case they were considered not to apply to this country, they were indicated with a minus (−). A question mark (?) was used to indicate that it was unknown whether the DBS apply to a particular country. The score 'not identified' applies to DBS that were identified in one or more of the three studied countries, but not in the international literature.

¹ Several studies (e.g. NERA Economic Consulting, 2009a,b) draw an analogy between pipelines carrying anthropogenic CO₂ and pipelines carrying other substances (mainly natural gas) due to the large overlap in design, construction and operation practices, which allows for the identification of DBS related to CO₂ pipelines. In this study, existing pipeline trajectories from which lessons are drawn for future CO₂ pipelines are referred to as 'analogue pipeline trajectories'.² This paper and cited research were conducted within the context of the COMET project, which aimed to identify and assess the most cost effective CO₂ transport and storage infrastructure able to serve the WMR. The COMET project was funded by the EU.

Table 1
Examples of drivers, synergies and barriers reported in literature.

	Examples	Reference
TECHNOLOGY		
Driver ^a	Technical knowledge/experience with hydrocarbon pipeline construction/operation	European Union (2012), Insight Economics (2011)
Barrier	Knowledge gaps on the corrosion effect of the impurities in CO ₂ streams.	Ramírez et al. (2011)
LEGISLATION/POLICY		
Driver ^a	Existing legislation and experience with legal procedures related to (conventional or CO ₂) pipeline transport and pipeline projects	Element Energy Limited (2010a), SSEB (2010)
Barrier	Inconsistency in countries' jurisdictions on technical standards of CO ₂ pipeline construction, operation and CO ₂ flows	Insight Economics (2011)
ECONOMICS/FINANCE		
Driver ^a	Re-use of captured CO ₂ in other markets (e.g. chemicals, biofuels, greenhouses, etc.)	Chrysostomidis and Zakkour (2008), Insight Economics (2011)
Synergy	Re-use of existing pipelines	Insight Economics (2011)
Barrier	Lack of economic incentives (e.g. CO ₂ price)	Chrysostomidis and Zakkour (2008), Sanders et al. (2013)
ORGANIZATION		
Driver ^a	Experience with organizational models of natural gas pipeline projects	Mikunda et al. (2011), SSEB (2010), Wu and Ramírez (2010)
Barrier	Knowledge gap on planning and organization of future CO ₂ pipeline networks	Element Energy Limited (2010c)

^a Note that the term 'driver' is not very strict and is often interchangeable with terms such as 'enabler', 'opportunity' or 'achievement' found in literature; nevertheless, it was decided to adhere to the term 'driver' throughout this study for the sake of consistency and clarity.

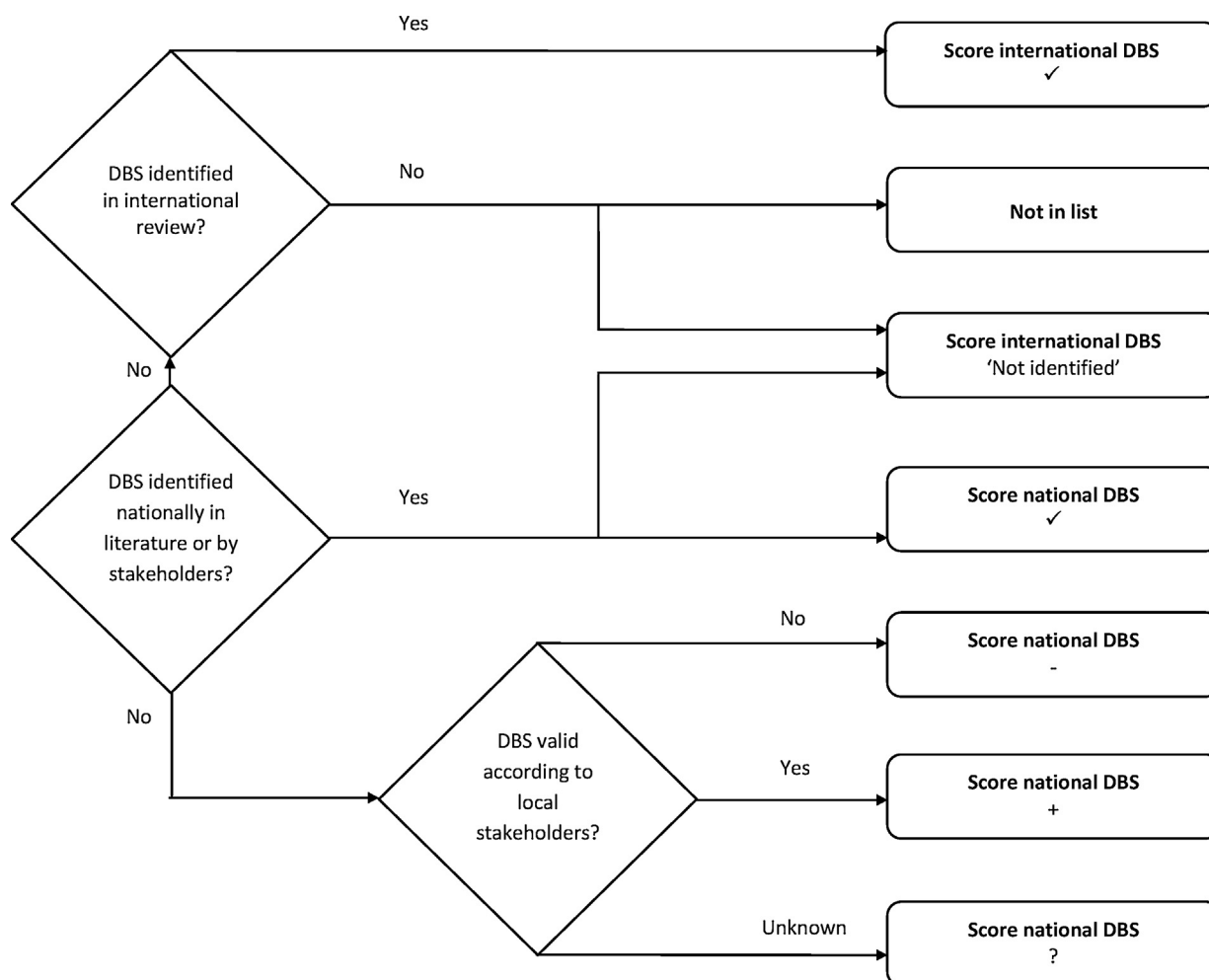


Fig. 1. Hierarchy for assigning scores to the drivers, barriers and synergies.

2.1.4. Data collection

The data collection comprised the following consecutive steps:

- An inventory of international literature to obtain an up-to-date overview of available knowledge on DBS related to the design,

construction and operation of CO₂ pipeline networks. The review covered studies from both academia and industry, with varying geographical scopes (country, regional and global level), and with a focus on the technological, legislative, political, economic, financial or organizational aspects of CO₂ pipelines or pipeline networks.

- An inventory of national literature comprising official policy and legal documents on (hydrocarbon) pipeline design, construction and operation, academic publications written in the local language, and if available, reports on local CCS projects. These sources provide information on, among others, embedded legislation, technical standards, routing, and organization of pipeline networks.
- Studying analogue pipeline trajectories (e.g. carrying hydrocarbons, water or CO₂) to provide new insight on DBS of pipelines. This step concerns mainly the collection of publicly available information.
- Interviews with stakeholders and experts involved in the design, construction and operation of the analogue pipeline trajectories to fill in remaining knowledge gaps and allow for a better understanding of important pipeline issues and solutions. Furthermore, the experts were asked about their expectations regarding future CO₂ pipelines in order to validate and complement the DBS identified in literature.
- Workshops with potential future stakeholders (e.g. energy and pipeline companies, government institutes) were organized in each of the countries under study. The aim of the workshops was to exchange information, ideas and visions on the preconditions of future CO₂ pipeline networks. Stakeholders were encouraged to ask questions, provide feedback and give information on the presented DBS.

2.1.8. Analysis of DBS of chosen infrastructure options

The results from the data collection and CO₂ pipeline networks were combined to identify route specific DBS. Whereas some DBS are rather generic (e.g. related to finance), several DBS can be related to the specific model results, such as oversizing of particular trunk CO₂ pipelines. The route specific DBS were identified for the pipeline network under several scenarios. Also, the uncertainty in the model results and its impact on the DBS are discussed.

2.2. Case study: Iberian Peninsula and Morocco

2.2.1. West Mediterranean region

Three CO₂ pipeline network scenarios were modelled for the WMR that differed with respect to: (1) whether CO₂ pipelines should follow existing pipelines (mainly natural gas) where available (Conservative CCS and Cross-frontier scenario), or not (Free-routes scenario), and (2) on the possibility to transport CO₂ across national borders (Cross-frontier scenario) or to restrict CO₂ transport to the country level (Conservative CCS and Free-routes

scenarios) (see Figs. 2–4). The pipeline network scenarios apply to the year 2030. Further information on the WMR case study and the three pipeline network scenarios can be found in Appendix A.

2.2.2. Data collection

An overview of the main international literature sources published over the period 2008–2012 is presented in Table 3. Studies published before 2008 were excluded from the inventory as they may contain outdated information on, for example, legislative issues.

Data on the national natural gas network were taken from government agencies (AICEP, 2008; CNE, 2013a,b), (EDP, 2009; REN, 2013), environmental impact assessments (Agrido Ambiente, 1995; Compostilla Project, 2013; Hidroprojecto, 2001; IMPACTE, 1997, 1996; Mikunda et al., 2011b; Ren, 2007; SEIA, 1995a,b, 1994), and academia (Relvas, 2008; Santos, 2011). Information on legislation was mainly taken from ERM Iberia (2004), Pöyry/Heymo (2011), Ren Gasodutos (2007).

Seven analogue pipeline trajectories were studied (see Table 2 and Fig. 5). The pipeline trajectories differ with respect to route, transported matter, length, and underground (onshore vs. offshore). Experts within the organizations involved in the analogue pipeline projects (Galp Energia; REN S.A.; CLC, Companhia Logística de Combustíveis; ENDESA; ENAGÁS) were contacted to collect additional information and make use of their knowledge, experience and expectations on CO₂ pipelines. An overview of the key technical features of the analogue pipeline trajectories can be found in Appendix B.

Several interviews were held with experts from companies. In Spain, a meeting was organized with the Spanish natural gas transport company ENAGÁS and the Spanish energy company ENDESA. The latter has also participated in the COMET project as industry partner contributing with its experience and knowledge based on OXY-300-CFB project in Compostilla. In Portugal, two meetings took place, one with two experts from REN Gasodutos S.A. (national natural gas transportation operator) and one meeting with Galp Energia and CLC (a group of Portuguese companies engaged in inter alia natural gas transport). In the results section, the interviews with Galp Energia, REN Gasodutos S.A., and ENDESA/ENAGÁS are referred to as interview 1, 2 and 3, respectively; detailed accounts of the interviews can be found in COMET (2012a), COMET (2012b) and COMET (2012c), respectively.

The workshops with local stakeholders (energy and pipeline companies, government institutes, industry, universities, and other organizations) were held in Marrakesh (1), Lisbon (2) and Madrid

Table 2
Analogue pipeline trajectories.

	Route	Transported matter	On-/offshore	Length (km)	Start year operation
I ^a	Sines–Setubal (Portugal)	Natural gas	Onshore	87	2003
II ^b	Setubal–Braga (Portugal)	Natural gas	Onshore	580	1997
III ^c	Braga (Portugal)–Tuy (Spain)	Natural gas	Onshore	76	1997
IV ^d	Sines–Aveiras de Cima (Portugal)	M.O.P. ^h	Onshore	147	1996
V ^e	Campo Maior–Leiria (Portugal)	Natural gas	Onshore	220	1997
VI ^f	Medgaz: Beni Saf (Algeria)–Almeria (Spain)	Natural gas	On-/offshore	210	2008
VII ^g	Compostilla–Santa María del Monte de Cea (Spain)	CO ₂	Onshore	140	Canceled ⁱ

^a Hidroprojecto (2001).

^b SEIA (1995a,b, 1994).

^c IMPACTE (1997, 1996).

^d Agrido Ambiente (1995).

^e REN (2007).

^f Mikunda et al. (2011b).

^g Compostilla Project (2013).

^h Multiple Oil Products

ⁱ The Spanish energy company ENDESA was awarded European Commission funding by the end of 2009 for the CCS Compostilla Project. The project involved the construction of three pilot plants to test capture, transport and storage technologies, which would be used as input for the construction of a demonstration plant by the end of 2015. The transport FEED study carried out for the Compostilla project was used as input for this study. By the end of 2013, it was decided not to proceed the project to the full scale demonstration stage (Foster Wheeler, 2013; GCCSI, 2014).



Fig. 2. CO₂ pipeline networks in the Conservative CCS scenario in 2030. The source and sink hubs represent the end points of the CO₂ pipelines. The geographical slopes, current natural gas pipelines, water bodies and protected areas are shown to illustrate potential interactions with the CO₂ pipelines. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)



Fig. 3. CO₂ pipeline networks in the Cross-frontier scenario in 2030. The source and sink hubs represent the end points of the CO₂ pipelines. The geographical slopes, current natural gas pipelines, water bodies and protected areas are shown to illustrate potential interactions with the CO₂ pipelines. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

Free-routes 2030



Fig. 4. CO₂ pipeline networks in the Free-routes scenario in 2030. The source and sink hubs represent the end points of the CO₂ pipelines. The geographical slopes, current natural gas pipelines, water bodies and protected areas are shown to illustrate potential interactions with the CO₂ pipelines. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

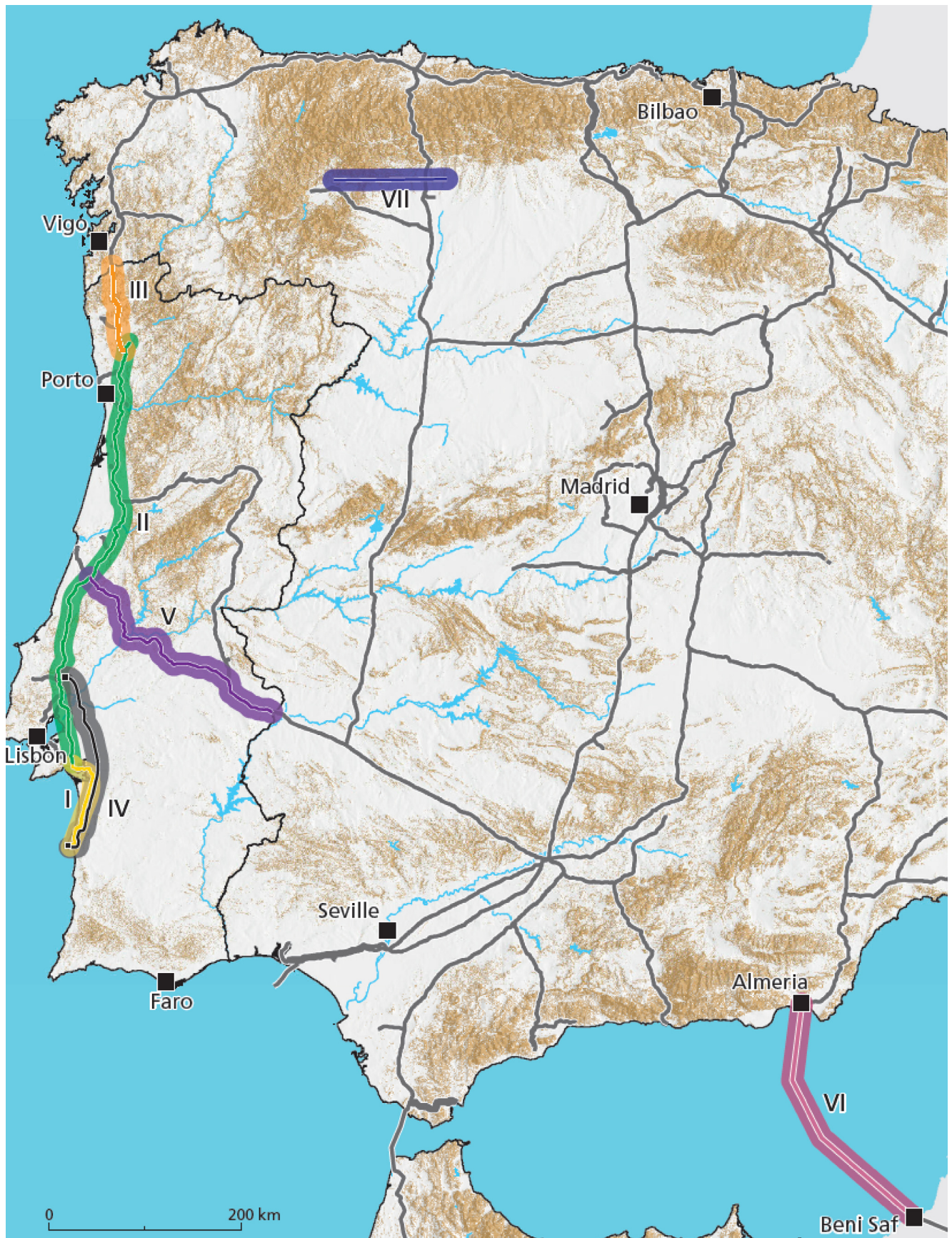


Fig. 5. Locations of analogue pipeline trajectories: (I) Sines–Setubal, (II) Setubal–Braga, (III) Braga–Tuy, (IV) Sines–Aveiras de Cima, (V) Campo Maior–Leiria, (VI) Medgaz: Beni Saf–Almeria, (VII) Compostilla–Santa María del Monte de Cea. The natural gas pipelines are indicated in grey. The Compostilla pipeline (VII) is presented as a straight line as the exact pipeline route is unknown.

Table 3
Overview of international literature on CO₂ pipeline transport (2008–2012) used for the inventory.

Study	Geographical Scope	Aspects covered				Method			
		Technology	Policy/ legislation	Economics/ finance	Organization	Desktop research	Analogue pipeline trajectories	Interviews with stakeholders	Workshops
Chrysostomidis and Zakkour (2008)	Worldwide		✓	✓	✓	✓	✓ ^a	✓ ^a	
ICF International (2009)	USA; Canada	✓	✓			✓		✓ ^b	
NERA Economic Consulting (2009a,b)	UK		✓	✓	✓	✓	✓ ^c		
Koornneef et al. (2010)	Worldwide	✓				✓			
Wu and Ramírez (2010)	Norway, UK, Denmark, Germany and the Netherlands		✓	✓	✓	✓			
Element Energy Limited, 2010b	Netherlands, Germany, Norway and the UK		✓			✓	✓ ^d	✓ ^d	✓ ^d
Element Energy Limited (2010a)	Worldwide	✓	✓	✓		✓			
SSEB (2010)	USA		✓	✓	✓	✓ ^e		✓ ^e	
DECC (2010)	UK		✓	✓		✓			
Element Energy Limited (2010c)	UK	✓	✓	✓	✓	✓		✓ ^f	✓ ^f
Insight Economics (2011)	Worldwide	✓	✓			✓			
Mikunda et al. (2011b)	Europe		✓		✓	✓		✓ ^g	✓ ^g
IEA (2011)	London Protocol contracting parties		✓			✓			
Mikunda et al. (2011a)	Mainly the Netherlands		✓	✓		✓	✓ ^h		
European Union (2012)	Denmark, Norway, Sweden		✓			✓			

^a The analysis was based on studies of pipelines transporting oil, gas and CO₂ and other large scale public infrastructure works as well as on interviews with potential financiers.^b Interviews with people involved in policy and commercial development of CO₂ pipeline transport.^c Studies on the British rail sector, British onshore gas networks, British electricity networks, UK offshore oil and gas networks, US interstate gas pipelines, English and Welsh water companies and German gas pipelines.^d The studies focused on (the role of governments in) large scale infrastructure projects (future CO₂ pipelines, hydrocarbon pipelines). The interviews and workshops involved more than forty stakeholders, including government, industry and academia.^e The data for this study were gathered through informal surveys, letters, personal interviews, site visits, and published reports.^f The analysis was based on interviews and workshops with more than forty stakeholders and experts.^g The analysis was based on interviews with members of gas transport operators and energy companies.^h Three transboundary natural gas pipeline trajectories were examined to identify legal issues.

(3). An overview of the stakeholders who attended the workshops can be found in [Appendix C](#). In the results section, the workshops are referred to as workshop 1,2 and 3; a detailed account of the workshops can be found in [Boavida et al. \(2012b\)](#).

3. Results

The DBS related to technology, legislation/policy, economics/finance and organization are presented in sections 3.1–3.4, respectively. Each section is divided into two subsections: drivers and synergies (1) and barriers (2). We ordered the DBS roughly from DBS with a potentially higher impact to lower impact. The findings include both DBS related to CCS in general and for CO₂ pipeline transport in particular. The latter can be divided into DBS related to CO₂ pipeline transport in general and for the specific pipeline routes in the model scenarios. The last group of DBS is further discussed in Section 3.5. The type of DBS is also indicated in the overview tables in each section.

3.1. Technology

An overview of the technological DBS is presented in [Table 4](#).

3.1.1. Drivers and synergies

- There is long worldwide experience with the design, construction and operation of both on- and offshore (high pressure) pipeline networks carrying natural gas and oil ([Element Energy Limited, 2010a](#); [European Union, 2012](#); [Insight Economics, 2011](#)), which could drive the deployment of CO₂ pipelines. Knowledge is available in all three countries on *onshore* pipelines. Both the study of analogue pipeline trajectories (see Section 3.2 and [Appendix B](#)) and local experts (workshop 3; interviews 1,2,3) indicated that Spanish stakeholders have detailed technical knowledge on the design, construction and operation of *offshore* pipelines.
- There is long worldwide experience with high pressure CO₂ pipeline transport – especially naturally occurring CO₂ from underground sources in North America – designated for enhanced oil recovery (EOR) ([Element Energy Limited, 2010a](#); [Insight Economics, 2011](#); [SSEB, 2010](#)).

3.1.2. Barriers

- Few engineers and professionals worldwide have the experience and skills to make appropriate designs for the transport of captured CO₂ ([Element Energy Limited, 2010a](#)), especially with respect to offshore transport over long distances. For that reason, demonstration projects are desirable to accumulate experience.
- The potential intermittency character of captured CO₂ flows poses challenges for pipeline transport operators. Significant fluctuations in CO₂ flows can lead to depressurization, temperature drop and phase changes, which can have an impact on the pipe's structural integrity, lead to solid CO₂ deposits forming plugs and metallurgical damage (embrittlement and fracture; damage to lining or coatings; ice coating in subsea pipelines) ([Ramírez et al., 2011](#)). Temperature and pressure buffers can only partly neutralize these effects. The operating philosophy including start-up and shut-down procedures developed for a point-to-point CO₂ pipeline designed for the ROAD CCS demonstration project in the Netherlands could be an example how to deal with the intermittency character ([Road CCS, 2013](#)). Additionally, more knowledge is needed on the thermodynamic behavior of CO₂ pipeline flows by doing (laboratory) research and developing sophisticated modeling tools ([Element Energy Limited, 2010a](#)). Although alleviation measures (e.g. matching supply and demand of CO₂; supply/off-take agreements; CO₂ storage tanks; start-up, shut-down, emergency and blowdown procedures; contingency

planning, or storage of gaseous CO₂ in the pipeline³) are available, these may increase the cost of CO₂ pipeline transport.

- Insufficient knowledge is available on the physicochemical properties of CO₂ flows containing impurities. Impurities can affect the pipeline transportation capacity, the CO₂ phase diagram, and the physical properties (e.g. viscosity, heat capacity, compressibility). Hence, certain CO₂ flows require a pipeline design that can withstand pipeline fracturing, hydrate formation, corrosion and two-phase flows ([Ramírez et al., 2011](#)). Although the basic CO₂ transport principles are understood, the interplay among the various impurities, their effect on the physicochemical properties of CO₂ and pipeline integrity is not completely clear yet. Furthermore, while technical measures are available to solve most of these problems (e.g. high grade steel, coatings), these may increase the costs of CO₂ transport considerably. Lessons need to be drawn from R&D programs set up to increase the knowledge base and bring down the costs of anthropogenic, dense phase CO₂ pipeline transport (such as COOLTRANS, CO₂ PipeHaz, SARCO₂, PIPETRANS).
- There is a knowledge gap on the probability of a CO₂ pipeline failure and the (fatal) impact it could have on human beings ([Koornneef et al., 2010](#); [Ramírez et al., 2011](#)). In the United States, 10 significant and 18 non-significant incidents⁴ with pipelines transporting naturally occurring CO₂ were observed in the period 1986 to mid-2003 ([PHMSA, 2013](#)), resulting in an estimated failure frequency of $6.3 \times 10^{-5} \text{ yr}^{-1} \text{ km}^{-1}$ and $1.75 \times 10^{-4} \text{ yr}^{-1} \text{ km}^{-1}$ for only significant and for both significant and non-significant incidents, respectively ([Knoope et al., 2014b](#)). However, the installed capacity is too low to derive reliable figures. Knoope et al. (2014b) argued that failure frequencies based on natural gas pipelines ($1.62 \times 10^{-4} \text{ yr}^{-1} \text{ km}^{-1}$ in the EU over the period 2006–2010; $1.05 \times 10^{-4} \text{ yr}^{-1} \text{ km}^{-1}$ in the U.S. over the period 1993–2012), which are often used in literature as a proxy for CO₂ pipelines, provide conservative (i.e. pessimistic) estimations. This is due to the fact that CO₂ pipelines will likely operate under more favorable conditions, like a larger wall thickness that makes them more resistant to external interference and corrosion. A study by the [Health and Safety Laboratory \(2009\)](#) suggest that CO₂ pipelines are safer, or at least as safe as natural gas pipelines. Knoope et al. (2014b) concluded that the risks of liquid CO₂ pipeline transport are most likely manageable and widely accepted under current legislative frameworks, even without risk mitigation measures (e.g. increasing soil coverage, concrete slabs, market tape). In addition, risk mitigation measures can be applied in densely populated areas, which will increase specific pipeline costs with around 4%. Gaseous CO₂ transport shows higher risks, especially for large mass flows, and requires considerable safety zones (100–770 meters depending on the mass flow and applied risk mitigation measures) to meet Dutch safety regulations ([Knoope et al., 2014b](#)). Several R&D programs include experiments with CO₂ pipelines to validate dispersion models and toxicity of CO₂ in order to provide a better understanding of the effects of a pipeline failure. More insight is needed on the

³ An example of a CO₂ pipeline using pressure swings to accommodate mismatches in supply and demand is the OCAP pipeline in the Netherlands. At night, CO₂ is stored in the pipeline, resulting in a pressure swing during the day from 20 bars in the morning to 10 bars by the end of the day ([RCI, 2009](#)). This example shows that there is scope for 'pipeline storage' in the gaseous phase; yet, confirmation for storage potential at higher pressures is required and merits further research.

⁴ PHMSA (2013) refers to significant incidents when any of the following consequences occur: "(i) fatality or injury requiring in-patient hospitalization; (ii) \$50,000 or more in total costs, measured in 1984 dollars; (iii) highly volatile liquid releases of 5 barrels or more or other liquid releases of 50 barrels or more; (iv) liquid releases resulting in an unintentional fire or explosion." The total costs of 50,000 \$1984 translate to around 80,000 €2010. The physical conditions (temperature, pressure) of a barrel were not indicated.

Table 4
Overview and comparison of drivers, synergies and barriers related to technology.^a

	Type of results	International literature	Spain	Portugal	Morocco
DRIVERS					
Long experience with designing, constructing and operating pipeline networks carrying natural gas and oil, both on- and offshore	GPT	✓	✓	✓ ^b	+
Experience with transport of CO ₂ (for EOR, chemical industry and food industry)	GPT	✓	✓	✓	+
BARRIERS					
Few engineers/professionals available that can make sound designs for safe transport of anthropogenic CO ₂	GPT	✓	+	+	✓
Knowledge gap on effect of intermittent flow character on the thermodynamic behaviour of CO ₂	GPT	✓	✓	✓	✓
Knowledge gap on effect of impurities on the physicochemical behaviour of CO ₂ and pipeline design	GPT	✓	✓	✓	✓
Knowledge gap on the probabilities and impacts of a pipeline failure.	GPT	✓	+	✓	+
Experience with (high-pressure) CO ₂ pipeline transport in Spain, Portugal and Morocco is virtually non-existent.	GPT	Not identified	✓	✓	✓
Lack of CO ₂ specific tools such as hydraulic CO ₂ simulators and commercial systems to control leakage.	GPT	✓	✓	+	+
Large altitude differences make the installation and maintenance of pipelines more difficult. Also insufficient knowledge is available on the effect of altitude on the properties of CO ₂ .	SPT	Not identified	✓	+	+
Laying CO ₂ pipelines in designated corridors in parallel to existing pipelines could be difficult or even technically impossible, because of spatial limitations	SPT	Not identified	✓	✓	+

^a The DBS are categorized in different types of results, namely: applying to CCS in general (GCCS), CO₂ pipeline transport in general (GPT), and specific CO₂ pipeline transport (SPT). The DBS actively identified in international literature or in a particular country are indicated with a tick (✓). In case the DBS were not actively identified by a local stakeholder and/or project partner, but was after discussion with local stakeholders confirmed or expected to apply to this particular country as well, is indicated with a plus (+). In case the DBS were considered not to apply to this country, they were indicated with a minus (−). A question mark (?) is used to indicate that it is unknown whether the DBS apply to a particular country. The score 'not identified' applies to DBS that were identified in one or more of the three studied countries, but not in the international literature. See also Section 2.1.3. ^b Although mainly Spanish companies are responsible for the pipeline infrastructure in Portugal, we consider that this knowledge is available in Portugal.

probability and effects of a CO₂ pipeline failure in order to take adequate and cost effective risk mitigation measures.

- Local stakeholders in Spain, Portugal and Morocco report that experience with CO₂ pipeline transport is virtually non-existent (workshops 1,2,3; interviews 1,2,3). CCS demonstration projects and knowledge transfer from abroad are therefore needed.
- CO₂ specific tools for modeling and leakage control to warrant safe and sound CO₂ pipeline transport are not yet developed. It is essential at that static and dynamic hydraulic simulators of variable composition CO₂ streams will make better projections of CO₂ flow behavior (interview 3).
- Geographical altitude differences are a determinant factor in the planning of a pipeline network (workshop 2, 3; interviews 1, 2). Mountainous terrains should be avoided to the extent possible so as to reduce technical difficulties and costs for design, construction and operation. Furthermore, the effect of altitude differences on the properties of CO₂ is rather unknown and requires further research (interviews 1,2,3).
- Laying CO₂ pipelines in designated corridors in parallel to existing pipelines could be difficult or even technically impossible, because of spatial limitations (workshop 2,3). To avoid delay during the construction phase, timely action is required by reserving space in pipeline corridors or land for alternative pipeline tracks.

3.2. Legislation and policy

The main findings of the legislative DBS are presented in Table 5.

3.2.1. Drivers and synergies

- The extensive legislative body on hydrocarbon pipeline transport constitutes a good basis for CO₂ pipeline transport. Both literature (e.g. [Element Energy Limited, 2010a](#); [SSEB, 2010](#)) and local

stakeholders (interviews 1,2,3) indicated that, if needed, existing legislation on hydrocarbon pipeline transport can be applied to fill in most of the regulatory gaps for CO₂ pipeline transport.

- The adoption of the EU CCS Directive 2009/31/EC governing inter alia third party access to pipeline networks, monitoring and reporting guidelines on CO₂ emissions and transboundary CO₂ transport, has been a major step in laying the legal foundation for CO₂ transport. This directive has been transposed to both Portuguese and Spanish law in the respective years 2012 and 2011 ([Shogenova et al., 2013](#)).
- Earmarking pipeline ventures as public interest projects can expedite legal procedures (interviews 1, 2, 3).
- In some cases, Right of Way (ROW) – i.e. an easement to use a strip of land for a particular purpose – of existing pipelines can be utilized for future CO₂ pipelines, which could avoid delay caused by legal procedures for acquiring new ROW (interviews 1,2,3). However, this is only possible if sufficient space is available for multiple pipelines (see Section 4.1).

3.2.2. Barriers

- There is a lack of clarity on (the interactions between) EU and national policy objectives related to CO₂ emission reductions, energy efficiency improvements and renewable energy targets, which causes confusion and uncertainty among stakeholders (workshop 3). In addition, uncertainty on policy on economic incentives (e.g. EU Emission Trading Scheme, CO₂ emission caps, taxes, public investments in CO₂ pipeline projects) for CCS in general and CO₂ pipeline transport in particular constitutes a major barrier (workshops 2,3; interviews 1,2,3). Governments publishing policy commitments or offering long term financial

Table 5Overview and comparison of drivers, synergies and barriers related to legislation and policy.^a

	Type of results	International literature	Spain	Portugal	Morocco
DRIVERS/SYNERGIES					
Use of existing legislation to fill existing gaps for codes and guidelines for transporting CO ₂	GPT	✓	✓	✓	+
Adoption of EU CCS Directive 2009/31/EC	GPT	✓	✓	✓	–
Earmarking CO ₂ pipeline ventures as public interest projects can expedite legal procedures, and thus, the implementation of CO ₂ pipeline projects	GPT	Not identified	✓	✓	+
If possible, the use of existing ROW facilitates the process of building new pipelines	GPT	Not identified	✓	✓ ^b	+
BARRIERS					
Lack of clarity and uncertainty on policy objectives on CO ₂ emission reductions, renewables, and energy efficiency as well as on economic incentives for CCS in general and CO ₂ pipeline transport in particular	GPCS/GPT	✓	✓	✓	✓
Several aspects of pipeline transport of anthropogenic CO ₂ designated for storage are not (sufficiently) covered in national law and regulations	GPT	✓	✓	✓	✓
Transboundary CO ₂ transport is currently not possible under London Protocol due to slow ratification process of the amendment of Article 6	GPT	✓	+	+	+
No explicit definition of captured anthropogenic CO ₂ in the Basel Convention	GPT	✓	+	+	+
National future legislation on CO ₂ transport can differ per country, thereby complicating transboundary transport	GPT	✓	✓	+	+
Liability for harm caused by accidents or leaks from CO ₂ pipelines or other transport facilities is unclear and creates uncertainty among potential pipeline owners and operators	GPT	✓	+	✓	+
Procedures to acquire ROW can be difficult and hamper a rapid build out of pipeline networks	GPT	✓	✓	✓	✓
Land use planning regulations obliging pipeline developers to avoid designated areas can result in additional costs and a delay in CO ₂ pipeline deployment	GPT	✓	✓	✓	✓
Lengthy permit procedures can delay a rapid build out of pipeline networks, especially if multiple countries with different permit procedures are involved	GPT	✓	+	✓	?
Establishing jurisdiction and responsibilities among national and local government actors is often difficult	GPT	Not identified	+	✓	?

^a The DBS are categorized in different types of results, namely: applying to CCS in general (GPCS), CO₂ pipeline transport in general (GPT), and specific CO₂ pipeline transport (SPT). The DBS actively identified in international literature or in a particular country are indicated with a tick (✓). In case the DBS were not actively identified by a local stakeholder and/or project partner, but was after discussion with local stakeholders confirmed or expected to apply to this particular country as well, is indicated with a plus (+). In case the DBS were considered not to apply to this country, they were indicated with a minus (–). A question mark (?) is used to indicate that it is unknown whether the DBS apply to a particular country. The score 'not identified' applies to DBS that were identified in one or more of the three studied countries, but not in the international literature. See also Section 2.1.3.

commitments would alleviate this uncertainty (Mikunda et al., 2011b).

- Several aspects of pipeline transport of anthropogenic CO₂ designated for storage are not (sufficiently) covered in national law and regulations. Det Norske Veritas (2010) published a recommended practice and set out basic specific codes for CO₂ pipeline design, construction and operation, which serves as a supplement to existing pipeline standards. Notwithstanding, several national regulations and acts have to be amended or clarified to encompass transport of anthropogenic CO₂. Furthermore, additional guidelines may have to be designed to fill in remaining regulatory gaps. Examples of issues not (sufficiently) addressed in national jurisdictions are health, safety and environmental aspects, standards for CO₂ stream conditions (e.g. acceptable impurity levels), siting of CO₂ pipelines, and procedures on tariff setting of pipeline capacity (Element Energy Limited, 2010a; European Union, 2012; Mikunda et al., 2011a; UCL, 2014) (interviews 1,2,3). More research is needed to identify the specific regulatory needs for Spain, Portugal and Morocco.
- Article 6 of the London Protocol prohibits contracting parties (incl. Spain, Portugal and Morocco) from allowing the export of wastes to other countries or dumping at sea. Article 6 was amended by contracting parties to allow transboundary CO₂

transport designated for sub-seabed storage, but requires ratification of two-third of the contracting parties (28 out of 42) to enter into force (Mikunda et al., 2011b; Warren, 2012). To date, only the UK and Norway have ratified the amendment, and it is unlikely that two-third of the parties will have ratified the amendment in the near term for a number of reasons, amongst others because CCS has a low priority for several contracting parties (Garrett and McCoy, 2013). Several legal solutions were proposed by an IEA working paper (IEA, 2011) to facilitate transboundary CO₂ transport based on the international rules of treaty interpretation. Garrett and McCoy (2013) considered that a provisional application of the Article 6 amendment would be the fastest and most straightforward solution. No studies or documents were found making statements on the expected period needed to solve this issue. As long as the London Protocol has not been ratified, transboundary CO₂ transport for the purpose of sub-seabed storage is prohibited.

- The Basel Convention (on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal) lacks a clear definition of captured CO₂ (Macrory et al., 2013). Uncertainty exists whether CO₂ should be classified as a hazardous substance or not. If CO₂ is classified as a hazardous waste, several barriers will arise on regard to transboundary CO₂ transport across states (Element Energy Limited, 2010a; Raine, 2008). For example, CO₂

export may only be allowed for countries that do not have storage capacity themselves, or cost increases and delays may occur due to the requirement to submit documents and notifications. Explicit definitions of CO₂ flows in terms of physicochemical properties (e.g. impurities, phase) during transport are needed to eliminate this uncertainty, and clarify the status of CO₂, either as a pollutant, commodity, or both. To the knowledge of Macrory et al. (2013), new definitions of CO₂ have not been made by any of the convention parties (incl. Spain, Portugal and Morocco). No studies or documents were found making statements on the expected period needed to solve this issue.

- Inconsistency in countries' jurisdictions on technical standards on CO₂ pipeline design, construction and operation (e.g. design and operating pressure, max. allowable impurity levels) as well as conditions on third party access to pipeline facilities could complicate transboundary CO₂ transport, both inside and outside the EU (Insight Economics, 2011). Moreover, state laws may conflict over pipeline control and management. Concerted action of governments is needed to solve cross-jurisdictional issues and align regulations to the extent possible. Another solution is the use of multi-lateral agreements between states and companies; today, such agreements are often used in transboundary pipeline projects to solve similar issues (Insight Economics, 2011; Mikunda et al., 2011a; World Bank, 2011).
- Liability for harm caused by accidents or leaks from CO₂ pipelines or other transport facilities is unclear and creates uncertainty among potential pipeline owners and operators (UCL, 2014) (interview 2). This topic should be addressed clearly in legislation.
- Procedures to acquire ROW can be difficult and hamper a rapid build out of pipeline networks. Acquiring ROW from too many land owners can be a major problem (interviews 1, 2; workshop 1). In Morocco, this is also due to the different types of property rights (incl. ancestral land), which makes the transfer of land from the original owners difficult. Financial incentives can help to alleviate this problem (workshop 1).
- Land use planning regulations pertaining to special areas – such as protected nature reserves, military zones and sites of historical or special interest – oblige pipeline developers to make detours, which can result in additional costs and a delay of the project (Element Energy Limited, 2010a). Examples of such regulations in Portugal are the Municipality Plans (e.g. notification N°6562/2010; notification no 11622/2012) (Municipality Coimbra, 2010; Municipality Lisbon, 2012), National Agricultural Reserve (Decree-Law no 73/2009) (MARDF, 2009) and National Ecological Reserve (Decree-Law 239/2012) (MASESP, 2012). Using planning and modelling tools in an early stage can help to identify cost effective solutions and avoid delay of the project.
- Lengthy permit procedures impede a fast implementation of CO₂ transport pipelines. Permit procedures can differ per country and land zone (residential vs. rural area) due to varying lead times, environmental regulations and possibility for third persons to appeal to a higher administrative court requesting a formal change to the official decision made. In case several countries are involved, project managers have to await the outcome of the slowest permit procedure (European Union, 2012). In Portugal, several provincial regions and municipalities crossed by a potential pipeline route have to give positive feedback on the project proposal, which is a very time consuming process (interview 2). Applying for permits in an early stage and labelling pipeline ventures as public interest projects can avoid delay of the project.
- Establishing jurisdiction and responsibilities on CO₂ pipelines among public administrations (e.g. national and local government actors) can be difficult. Close communication among different government levels is therefore important (interview 3).

3.3. Economics and finance

The main findings of the economic and financial DBS are presented in Table 6.

3.3.1. Drivers and synergies

- The main economic driver relates to a national or international financial-regulatory framework (e.g. emission trading scheme (ETS), carbon tax, favourable loans, tax incentives) to create a market for CCS (Element Energy Limited, 2010a; European Union, 2012; Insight Economics, 2011).
- Economic revenues can be created by utilizing captured CO₂ for EOR, greenhouses, food and chemical industry and biofuel production (Chrysostomidis and Zakkour, 2008; Insight Economics, 2011). Although several experts expected the potential for CO₂ utilization in the WMR to be limited (workshops 2 and 3), research is needed to determine whether such opportunities exist or not, especially for greenhouses in the Spanish horticulture sector.
- Future CO₂ pipeline projects can benefit from the large experience accumulated by energy firms and project developers with investments models for natural gas and oil pipeline networks (SSEB, 2010) (interviews 2, 3). An extensive overview of available investment models available for CO₂ pipelines can be found in Chrysostomidis and Zakkour (2008).
- Economic synergies can be achieved by oversizing CO₂ trunk pipelines or amalgamating demand for pipeline capacity to exploit economies of scale (Chrysostomidis and Zakkour, 2008; Mikunda et al., 2011b). Knoope et al. (2014a) showed that oversizing of CO₂ trunk pipelines is economically interesting in case the oversized capacity is used not later than five to ten years after the construction of the pipeline⁵.
- The re-use of existing pipelines for CO₂ transport can save significant investment cost⁶ (Insight Economics, 2011). However, the potential for re-use of existing pipelines is expected to be minor in the WMR (workshops 2,3; interviews 1,2,3).
- In case CO₂ pipelines can be installed parallel to other pipelines, bundling monitoring and maintenance activities can reduce costs significantly (interviews 1,3).

3.3.2. Barriers

- In total, eight economic/financial barriers were identified, of which four in international literature.
- The current low CO₂ price and the uncertainty on future CO₂ prices and government's commitments to EU CO₂ emission allowances render it impossible to make a robust business case for CCS (Chrysostomidis and Zakkour, 2008; Sanders et al., 2013) (interviews 1,2,3). A possible solution is to reform the ETS by reducing the number of emission allowances in order to increase the CO₂ price and create a market for CCS (ZEP, 2013).
- The high level and high risk profile of investments in a CO₂ pipeline (network) is considered to be one of the main economic barriers (Chrysostomidis and Zakkour, 2008; Sanders et al., 2013) (interviews 1,2,3). The uncertainties on the technological feasibility, economic revenues, policy, legislation, market development and public acceptance is deemed unacceptable by investors (Sanders et al., 2013). The government could reduce uncertainty by settling outstanding legal issues and make clear (legally binding) commitments on CCS for the future. Furthermore, the

⁵ This statement holds for two equal sized point sources in close proximity to each other (10 km) and using a real discount rate of 10%.

⁶ The possibilities for re-use depend on many factors, such as the design pressure of the existing pipeline, capacity, impurities in the CO₂ stream, pipeline materials, remaining service life and availability of the pipeline.

Table 6Overview and comparison of drivers, synergies and barriers related to economics and finance.^a

	Type of results	International literature	Spain	Portugal	Morocco
DRIVERS/SYNERGIES					
Financial-regulatory framework including for example: ETS, carbon tax, beneficial discount rates, tax incentives, subsidies at local, regional, national and international level	GCCS	✓	+	✓	+
The use of CO ₂ for the production of synthetic methane, enhanced hydrocarbon recovery, greenhouses, food and chemical industry and biofuel production can drive the market for CCS	GCCS	✓	+	✓	+
Large experience of energy companies and project developers with investments models for the development of natural gas and oil pipeline networks	GPT	✓	✓	✓	+
Oversizing pipelines or amalgamating demand for pipeline capacity to exploit economies of scale	SPT	✓	+	✓	+
Bundling monitoring and maintenance activities when CO ₂ pipelines can be installed parallel to other pipelines can reduce costs	SPT	Not identified	✓	✓	+
Re-use of existing pipelines to reduce costs for materials and construction	SPT	✓	+	+	+
BARRIERS					
The low price of CO ₂ makes it virtually impossible to make a robust business case for CCS	GCCS	✓	✓	✓	+
High level and risk profile of investments in CO ₂ transport infrastructure is often considered to be unacceptable by private investors	GPT	✓	✓	✓	+
Uncertainty on future CO ₂ pipeline demand is a barrier to private firms oversizing CO ₂ transport pipelines	GPT	✓	+	+	+
The economic crisis delays CCS demonstration projects, which are needed to reduce the (perceived) risk for investors	GPT	Not identified	✓	+	+
Geographical altitude differences can increase the costs of CO ₂ transport significantly	SPT	Not identified	✓	✓	+
Need for an electric infrastructure for the booster stations to repressurize the CO ₂	GPT	Not identified	✓	✓	+
Private investors may delay or even refrain from investing in CO ₂ pipelines due to the risk of high and variable steel prices	GPT	✓	✓	+	+
Taxes levied in different Moroccan administrative areas could increase the costs of transport significantly	GPT	Not identified	–	–	✓

^a The DBS are categorized in different types of results, namely: applying to CCS in general (GCCS), CO₂ pipeline transport in general (GPT), and specific CO₂ pipeline transport (SPT). The DBS actively identified in international literature or in a particular country are indicated with a tick (✓). In case the DBS were not actively identified by a local stakeholder and/or project partner, but was after discussion with local stakeholders confirmed or expected to apply to this particular country as well, is indicated with a plus (+). In case the DBS were considered not to apply to this country, they were indicated with a minus (–). A question mark (?) is used to indicate that it is unknown whether the DBS apply to a particular country. The score 'not identified' applies to DBS that were identified in one or more of the three studied countries, but not in the international literature. See also Section 2.1.3.

establishment of a strong, well-functioning financial-regulatory framework and the provision of financial guarantees to private investors are needed to safeguard their investments (Element Energy Limited, 2010a).

- Private investors may refrain from oversizing CO₂ pipelines due to the risk of low demand for CO₂ pipeline capacity in the future. This could result in higher total investment cost for pipeline capacity from a societal point of view as economies of scale will not be fully exploited (Chrysostomidis and Zakkour, 2008; Mikunda et al., 2011b). Governments could alleviate this problem by promoting investors to amalgamate their demand for pipeline capacity by, for example, obliging project developers to hold open seasons⁷, and making explicit agreements on future usage of the pipeline. Other possible options are public or public-private finance constructions and financial rewards for shareholders and/or private investors who are exposed to the risk of future pipeline demand (Chrysostomidis and Zakkour, 2008; Mikunda et al., 2011b). Striking the right balance between risk, revenues

and the sources of finance is quintessential in creating a commercially viable CO₂ network (Chrysostomidis and Zakkour, 2008; Mikunda et al., 2011b).

- The economic crisis has had a delaying effect on the deployment of CCS demonstration projects, which are needed to demonstrate the technological feasibility of the entire CCS chain (including CO₂ pipeline transport) (interviews 1,2,3).
- Large geographical altitude differences in the WMR are a country-specific barrier (interview 3; workshops 2,3). Running pipelines across mountainous areas could significantly increase the cost of CO₂ pipeline transport due to large pressure drops, and should therefore be avoided to the extent possible. Higher operating pipeline pressures were suggested for Spain so as to avoid the need for booster stations along pipeline routes (interview 3).
- Natural gas pipelines can deliver their own energy to booster stations along pipeline routes, which are needed to repressurize the transported gas. However, CO₂ pipelines would require an electric infrastructure to power the booster stations. Installing such an infrastructure would increase the cost of a CO₂ pipeline network considerably, especially in remote areas without direct access to electric power sources (interviews 1,2,3).
- Private investors may delay or even refrain from investing in CO₂ pipelines due to the risk of high and variable steel prices,

⁷ In an open season, a pipeline project developer makes it possible for other parties in the market to join the project. Open seasons act as an insurance that pipeline project developers provide an efficient level of capacity and exploit economies of scale.

Table 7Overview and comparison of drivers, synergies and barriers related to organization.^a

	Type of results	International literature	Spain	Portugal	Morocco
DRIVERS/SYNERGIES					
Experience with organizational models of natural gas pipeline projects crossing international borders, which provides valuable lessons on issues such as permitting, construction and operation of the pipeline infrastructure spanning national borders	GPT	✓	✓	✓	+
BARRIERS					
Differences in countries' organizational models of transport networks may constitute a barrier for future transboundary CO ₂ transport networks	GPT	✓	✓	✓	+
Insufficient planning and communication among stakeholders and countries could result in a sub-optimal buildout, delay and increased costs of a CO ₂ pipeline network	GPT	✓	+	+	+
Insufficient scheduling between the pipeline network and CO ₂ capture in industries and power plants could become a barrier. Scheduling among the different parts of the CCS infrastructure is essential	GPT	✓	+	✓	+
The complicated relationships between regions within a country could make CO ₂ pipeline transport from one region to the other problematic	GPT	Not identified	✓	–	?

^a The DBS are categorized in different types of results, namely: applying to CCS in general (GCCS), CO₂ pipeline transport in general (GPT), and specific CO₂ pipeline transport (SPT). The DBS actively identified in international literature or in a particular country are indicated with a tick (✓). In case the DBS were not actively identified by a local stakeholder and/or project partner, but was after discussion with local stakeholders confirmed or expected to apply to this particular country as well, is indicated with a plus (+). In case the DBS were considered not to apply to this country, they were indicated with a minus (–). A question mark (?) is used to indicate that it is unknown whether the DBS apply to a particular country. The score 'not identified' applies to DBS that were identified in one or more of the three studied countries, but not in the international literature. See also Section 2.1.3.

which have a large impact on the total pipeline cost (interview 3). Long term contracts can reduce uncertainties of steel price fluctuations.

- The taxes levied in Moroccan administrative areas could increase the costs of CO₂ pipeline transport significantly (workshop 1). Early insight into potential administrative costs is required to estimate the financial feasibility of CCS projects.

3.4. Organization

The main findings of the legislative DBS are presented in Table 7.

3.4.1. Drivers and synergies

- The wide experience with organizational models of natural gas pipeline projects provides valuable lessons on the design, construction and operation of pipeline infrastructures spanning national borders (Chrysostomidis and Zakkour, 2008; Mikunda et al., 2011b; Van den Broek et al., 2010; Wu and Ramírez, 2010) (interviews 1,2,3). Groenenberg and Buit (2009) distinguish three organization models, each with its own merits and demerits: public ownership, private ownership and public-private partnership (PPP). A PPP, which is an organizational model involving a contract between government and private parties to develop and operate public services, is often considered most valuable for large scale projects serving a public good, such as a future CO₂ pipeline infrastructure, as it combines the safety of services due to public ownership and the working efficiency of the private sector (Groenenberg and Buit, 2009; Van den Broek et al., 2010; Wu and Ramírez, 2010).

3.4.2. Barriers

- The establishment of a CO₂ pipeline network spanning national borders could be difficult in case there will be inconsistencies in the countries' organizational CO₂ pipeline models. Experience with transboundary natural gas pipeline projects provides valuable lessons. For example, in several natural gas pipeline projects, a commission representing the governments of both countries was appointed to oversee and facilitate the resolution

of transboundary issues (Interconnector, 2012). Furthermore, governments could anticipate on this issue by making multilateral agreements on tariff setting as well as by collaborating on other organizational issues for transboundary pipeline networks (Element Energy Limited, 2010b).

- Insufficient planning and communication among stakeholders and countries could result in a sub-optimal buildout, delay and increased costs of a CO₂ pipeline network (Element Energy Limited, 2010b; Wu and Ramírez, 2010). Governments could prevent such a scenario by promoting efficient pipeline investment (see Section 4.3), network integration (e.g. oblige pipeline developers to provide technical possibilities for future pipeline connections) and efficient use of pipeline capacity via unbundling of ownership and operation, setting a fair tariff structure, and establishing a transparent secondary trading platform for pipeline capacity (NERA Economic Consulting, 2009a).
- Insufficient scheduling between pipeline network developers and CO₂ capture operators in the industrial and power sectors could be a potential barrier (Element Energy Limited, 2010a) (interview 2). Working out a master plan for the deployment of a large-scale CCS network in and across the WMR is, therefore, of key importance.
- The complicated relationships between different Spanish regions could make CO₂ pipeline transport from one region to the other problematic. Storing one region's CO₂ in another region could be perceived as waste dumping and stir up tensions. Possible solutions should focus on providing information and facilitating communication among the regions involved as well as on financial compensations from the emitter to the storage regions (interview 3).

3.5. Route specific drivers, barriers and synergies

3.5.1. Synergies through utilization of existing ROW and sharing costs between parallel pipelines

The CO₂ pipeline networks in the three scenarios show several potential opportunities for legal and economic synergies by laying CO₂ pipelines parallel to natural gas pipelines (see red and

Table 8

Pipeline tracks with potential opportunity for utilizing existing ROW and sharing costs between CO₂ and natural gas pipelines. The connections are also indicated in Fig. 3. CS, CFS and FRS stand for the Conservative CCS, Cross-frontier and Free-routes scenario, respectively.

Route	Connections	Scenarios	Rough estimate distance (km)
Spain			
Ribadeo–Oviedo	I	CS,CFS,FRS	100
Tudela–Zaragoza	II	CS,CFS,FRS	50
Benlloch–Sagunt	III	CS,CFS	100
Urda–Puertollano	IV	CS,CFS,FRS	100
Portugal			
Porto–Aveiro	V	CS,CFS,FRS	50

Table 9

CO₂ pipelines with opportunity for oversizing. The connections are also indicated in Fig. 3. CS, CFS and FRS stand for the Conservative CCS, Cross frontier and Free-routes scenario, respectively.

Route	Connections	Scenarios	Rough estimate distance (km)
Spain			
San Sebastián–Logroño	a	CS,CFS,FRS	100
Bilbao–San Sebastián	b	CS,CFS	100
San Esteban de Gormaz–Andorra (city)	c	CS,CFS	300
Barcelona–Valencia	d	CS,CFS	300
Aranjuez–Puertollano	e	CFS,FRS	100
Huelva–Mengíbar	f	CS,FRS	300
Tarragona–Escatron	g	CFS	200
Morocco			
Rabat–Tetouan/Ceuta	h	CFS	200
Transboundary			
Abrantes (Portugal)–Córdoba (Spain)	i	CFS	400

black lines running parallel in Figs. 2–4). However, as mentioned before, the possibility to exploit these synergies is dependent on site-specific conditions; further research is required to identify specific tracks where these synergies can be exploited. Table 8 presents a list of joint natural gas and CO₂ pipeline tracks in Spain and Portugal for distances of fifty kilometers or longer. However, several other joint tracks with shorter distances (<50 km) can be observed in Figs. 2–4. Table 8 shows that most joint pipeline tracks were identified for all three scenarios, thus irrespective of the CO₂ mitigation level, storage capacity potential and possibility of transboundary CO₂ transport. No joint pipeline tracks were identified for Morocco. It should be noted that from a cost perspective following natural gas pipelines is not by definition the least cost pipeline network solution. This is shown by the investment cost of the pipeline network, which is lower in the Free-routes scenario than in the other two scenarios (see Appendix A).

3.5.2. Oversizing of CO₂ pipelines to exploit economies of scale

Table 9 gives an overview of CO₂ pipelines eligible for oversizing in the three scenarios to exploit economies of scale. The pipeline running from San Sebastián to Logroño is oversized in all three scenarios; the other pipelines are oversized in one or two scenarios. The pipelines should be oversized during the design and construction; this is before 2030 for all pipelines except for the pipeline running from Aranjuez to Puertollano, which should be in operation in 2040.

Table 10

CO₂ pipeline tracks with geographical altitude differences. The connections are also indicated in Fig. 3. CS, CFS and FRS stand for the Conservative CCS, Cross frontier and Free-routes scenario, respectively.

Route	Connections	Scenarios	Rough estimate distance (km)
Spain			
Asturias–León	1	CS,CFS	100
Vizcaya–Guipuzcoa	2	CS,CFS	100
South of Cantabria	3	CS,CFS	50
San Sibrao–Ponferrada	4	FRS	50
Vizcaya–Alava	5	FRS	50

3.5.3. Water bodies and land use planning regulations of special areas

Water bodies and land use planning regulations pertaining to special areas result in high costs for crossing these areas or even obliges pipeline developers to make detours, which can also result in additional costs and a delay of project deployment (see Section 4.2). Water bodies and protected nature reserves are marked with blue and green areas in Figs. 2–4, respectively. An example of a pipeline crossing an estuary is the Sines–Setúbal pipeline in Portugal in the Conservative CCS and Cross-frontier scenarios in 2030, which is a protected area (Natural Reserve of the Sado Estuary); and also Parque Natural da Arrábida (where a cement plant is located). Water bodies (e.g. rivers and estuaries) are crossed several times as these are more difficult to avoid.

3.5.4. Geographical altitude differences

Mountain crossings are mainly observed in the Cantabrian Mountains (north of Spain) between Asturias and León, south of the province Cantabria, and between Vizcaya and Guipuzcoa (Spain) in the Conservative CCS and Cross-frontier scenarios; in the Free-routes scenario, mountain crossings are observed between San Sibrao and Ponferrada in León, and Vizcaya and Alava (see Table 10). Installation and operation of CO₂ pipelines and power supply will be expensive along these CO₂ pipeline tracks.

4. Discussion

The research resulted in a comprehensive list of DBS that is considered to be quite exhaustive, because of the various ways of data collection. For this reason, the method proved to be an effective way to identify DBS for a pipeline infrastructure. However, a caveat is issued in relation to the route-specific DBS, which depend strongly on the pipeline modelling results and are thus rather uncertain. Despite this generic uncertainty, several pipeline routes occur in all three scenarios and are, therefore, likely to be installed in case CCS is deployed at a large scale across the region. Further research should aim to identify for which parts of these pipeline routes, ROW can already be acquired, and, if sufficient space is available in the pipeline corridors, where ROW of natural gas pipelines can be used for the CO₂ pipelines to avoid unnecessary delays and exploit cost synergies. Albeit crossings of mountains, nature areas and water bodies were discouraged in the modelling work, several crossings can be observed in the pipeline networks (see Section 4.5). Where possible, alternative routes could be considered on a case-by-case basis; for example, by deviating from the natural gas pipeline tracks in the CS and CFS scenarios, several barriers can be avoided (see Section 4.5). Furthermore, in due time, assessments should be made for which CO₂ trunk pipelines that show opportunities for capacity oversizing to exploit economies of scale (e.g. between San Sebastián to Logroño in the north of Spain), oversizing is indeed economically interesting. To this end, the CO₂ pipeline design criteria of Knoop et al. (2014a) could be used, which allows for a more detailed techno-economic optimization analysis of CO₂ pipeline configurations, including pipeline oversizing. Next to the route-specific DBS, several other issues were identified that merit further research:

- In the COMET model, the contribution of the individual CO₂ source clusters to the national sector emissions were assumed to remain constant over the modelling period. More insight is needed on the development of cluster development as well as on the advent and location of new industries to improve the modelling of sector emissions and pipeline networks. Similarly, exploration of the CO₂ storage sites is required at an early stage to validate the values used in the COMET model for the characteristics (e.g. injection rate) and potential of the individual sites.
- The data collection in Morocco was rather difficult. More research is needed to identify potential remaining DBS in Morocco and validate the country specific DBS for the Moroccan case, especially by studying analogue pipeline trajectories and doing interviews with local stakeholders. Although the modeling results of (Kanudia et al., 2013, 2012c,d) show only few CO₂ pipelines in Morocco (Figs. 2–4), more could follow in case further research would confirm expectations on the large offshore CO₂ storage potential, which is currently unknown due to limited (publicly) available data (Martínez and Carneiro, 2011).
- Albeit offshore and transboundary pipeline transport plays only a minor role in the modelled pipeline networks, it is recommended to anticipate on potential DBS related to these topics, such as cross-jurisdictional issues, by investigating them beforehand. Improved input data quality for the COMET model, including on the storage potential on the Moroccan continental shelf and other parts of North Africa, could result in more offshore and transboundary pipeline transport, thereby making these topics more relevant.
- Geske et al. (2015a,b) show that CO₂ shipping can be a cost effective alternative for certain offshore pipeline routes, especially for transport of small volumes and over long distances. Furthermore, ships have the advantage of flexibility, which could be especially interesting in the early stages of the CCS market. Therefore, the

DBS of the CO₂ shipping option should be further investigated to explore the practical feasibility of this transport mode.

- Ways to engage the local public, politics and NGOs in the process of designing the CCS infrastructure should be assessed so that their points of view can be optimally incorporated in this process (see e.g. Terwel et al., 2012). Further research is desirable to identify fruitful modes of engagement.

5. Conclusions

Conclusions

This study provided a method to identify drivers, barriers and synergies (DBS) related to the deployment of a regional CO₂ pipeline network. The method was demonstrated for the West Mediterranean region (WMR) and is related to other research carried out in the COMET project (Boavida et al., 2013; Gouveia et al., 2013; Kanudia et al., 2013; Van den Broek et al., 2013b), in which several possible CO₂ pipeline networks were modelled under three scenarios that differed with respect to: (i) whether CO₂ pipelines should follow existing pipelines (mainly natural gas) where available (Conservative CCS and Cross-frontier scenario), or not (Free-routes scenario), and (ii) on the possibility to transport CO₂ across national borders (Cross-frontier scenario) or to restrict CO₂ transport to the country level (Conservative CCS and Free-routes scenarios).

The first part of the method comprised a literature review, an analysis of embedded hydrocarbon and CO₂ pipeline trajectories, interviews with pipeline experts, and workshops with stakeholders. Subsequently, the collected information was used to identify route specific DBS in the modelled CO₂ pipeline networks. Finally, where applicable actions were identified that could alleviate the barriers or take advantage of the synergies and drivers. The research resulted in a comprehensive list of DBS for the WMR case study, which is expected to be quite exhaustive, because of the various ways of data collection. Furthermore, the list provides a framework for action. For these reasons, the method proves to be an effective way to identify DBS for a pipeline infrastructure, also in other parts of the world.

Based on the WMR case study an extensive list of DBS has been compiled. The identified barriers can in principle be tackled to make the design, construction and operation of a CO₂ pipeline network possible. Furthermore, there are opportunities for cost reductions and facilitating processes as well. Most of the DBS can and should be addressed at an early stage to enable CO₂ pipeline transport in the future. The DBS are related to CCS and CO₂ pipeline transport in general as well as to the specific pipeline routes in the modelled scenarios.

The main drivers/synergies identified in both literature and by local stakeholders applying to CO₂ pipeline networks in general are the long experience with natural gas pipeline transport, embedded legislation, existing investment and organizational models for hydrocarbon pipeline networks, and oversizing pipelines to exploit economies of scale. Portuguese and Spanish stakeholders added that earmarking CO₂ pipeline ventures as public interest projects can expedite the implementation of CO₂ pipeline projects. Most route specific drivers and synergies apply to all three scenarios, although not always to the same extent. The CO₂ sources and sinks in the WMR are located far from each other. There are several opportunities to lay CO₂ pipelines along existing pipelines, provided sufficient space is available in the pipeline corridors, thus creating opportunities to reduce costs and utilize existing Right of Way. However, the Free-routes scenario shows that it is not necessarily cheaper to follow natural gas pipelines, because deviating from the natural gas pipelines can reduce the CO₂ pipeline distances

considerably. These cost considerations may affect the eventual routing of the pipeline networks. Another potential synergy can be achieved by oversizing (trunk) CO₂ pipelines to exploit economies of scale in case the oversized capacity is used not later than five to ten years after the construction of the pipeline.

The main technological barriers applying to CO₂ pipeline networks in general are the knowledge gaps on the (cost increasing) effect of impurities and intermittent flow patterns on the physicochemical properties of the CO₂ flow during pipeline transport as well as on the probability and impact of a CO₂ pipeline failure. Other main barriers are the lack of specific legislation on CO₂ pipeline transport, lengthy permit procedures, land use planning regulations, uncertainty of future climate policy, lack of financial incentives, high level and risk profile of CO₂ pipeline investments, the economic crisis, and the need for an electric infrastructure to power booster stations. The technical and economic route specific barriers relate to crossings of water bodies and mountainous areas as well as land use planning regulations of special areas. The Cross-frontier scenario shows specific barriers related to unresolved issues in international conventions (e.g. London Protocol and Basel Convention) and different jurisdictions and organizational models of transport networks between countries, which currently hamper transboundary CO₂ transport. Although many barriers were identified, most of these barriers (e.g. technical knowledge gaps, outstanding legislative issues, lack of financial incentive) can, in principle, be tackled.

7.2. Policy implications

Most DBS identified in this study are generic, i.e. they apply to CO₂ pipeline transport in general and are not route specific. The DBS list provides a framework for action comprising short term measures related to different aspects of pipeline infrastructure, namely technology (i), legislation/policy (ii, iii), economics/finance (iv, v) and organization (vi). The key measures are: (i) stimulating research and CCS demonstration projects to investigate remaining technical knowledge gaps (e.g. effect of impurities in and intermittency of CO₂ flows) and prove the techno-economic feasibility of CCS; (ii) formulating consistent and transparent policy regarding CCS; (iii) resolving outstanding legal issues in international treaties and establishing a transparent national and regional (preferably on EU level) legislative framework to enable CO₂ pipeline transport. Concerted action and involvement of private and public stakeholders (also between countries) are key to create a broadly supported and coherent legislative framework; (iv) establishing a (European wide), well-functioning financial regulatory framework (e.g. ETS or a carbon tax) to make a sound business case for CCS possible; (v) devising financial programs to supply potential investors in CO₂ pipeline infrastructure with funding resources and low risk exposure; (vi) scheduling and communication among stakeholders and countries involved in different parts of the CCS chain to avoid delay and sub-optimal infrastructure deployment.

The route specific DBS in the WMR case study are more relevant for the mid-long term. Mid-long term measures should focus on the preparation of public utility declarations and permits for the crossings of nature reserves, the acquisition of ROW and pipeline oversizing. More research is needed to identify for which parts of the identified pipeline routes these measures should be taken.

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Appendix A. West Mediterranean region

This appendix describes the case study of the Iberian Peninsula and Morocco that was used for the analysis in this paper.

West Mediterranean region

The WMR shows potential for CCS considering its large CO₂ storage capacity, especially in Spain (GCCSI, 2012). An inventory was made of the CO₂ point sources and storage locations across the WMR by Boavida and Sardinha (2012), Boavida et al. (2012a), Martínez and Carneiro (2011).

The map in Fig. A1 shows the 285 stationary CO₂ point sources across the region over the period 2005–2009. The point sources are made up of utilities, oil refineries, cement, iron and steel, pulp and paper and other industries. Note that Spain accounts for more than 70% of the point sources (221) and CO₂ emissions (153 MtCO₂/y) in the three countries. The Spanish point sources are spread all over the country. Portugal and Morocco show similar features in number of point sources (35 and 29, respectively) and emitted CO₂ (both around 28 MtCO₂/y) (Mesquita and Carneiro, 2013). Both the Portuguese and Moroccan point sources are predominantly located in the coastal areas.

The map in Fig. A2 provides an overview of the locations and storage potential of the CO₂ injection sites across the WMR. The total storage capacity amounts to nearly 30 GtCO₂, which is divided over a number of 163 storage structures. Spain has the largest estimated storage capacity (around 22 GtCO₂, 118 structures), followed by Portugal (7.5 GtCO₂, 36 structures) and Morocco (0.4 GtCO₂, 9 structures) (Mesquita et al., 2013). Storage structures with a capacity less than 3 MtCO₂ were excluded from the inventory, nor are they shown in Fig. A2.

8. Scenarios and CO₂ pipeline networks for the West Mediterranean region

Eight scenarios were devised for the WMR for the time period 2010–2050 with different assumptions on gross domestic production (GDP) growth and concomitant CO₂ emissions, CO₂ emission reduction levels, CCS availability, storage potential, CO₂ pipeline networks, and the possibility to transport CO₂ across country borders (see Gouveia et al., 2013). For the design of the pipeline networks, both the CO₂ point sources and sinks were clustered together to reduce the number of pipelines and exploit economies of scale (see Figs. A1 and A2). The hubs of the source and sink clusters were connected in a most cost effective way for each scenario.

Three of the eight aforementioned scenarios differ with respect to assumptions made on the CO₂ pipeline network; hence, the focus in this study was on these three scenarios. The assumptions differ on (1) whether CO₂ pipelines should follow existing pipelines (mainly natural gas) where available (Conservative CCS and Cross-frontier), or not (Free-routes), and (2) on the possibility to transport CO₂ across national borders (Cross-frontier) or to restrict CO₂ transport to the country level (Conservative CCS and Free-routes). These three scenarios assume an annual GDP growth over the coming forty years (Spain: 2.4%/y; Portugal: 2.0%/y; Morocco: 3.6%/y)⁸, a national CO₂ emission target of 40% below 2005 levels in 2050, and the technical and economic availability of CCS from 2020 onwards.

⁸ The annual GDP growth rates were mainly based on projections of the International Monetary Fund (IMF, 2012). However, the projections for Spain and Portugal could be regarded as too optimistic considering the current economic crisis. In the COMET model, a scenario with a low GDP growth was run as well (see Kanudia et al., 2013). It was found that with low economic growth assumptions CCS remains competitive but the market is reduced.

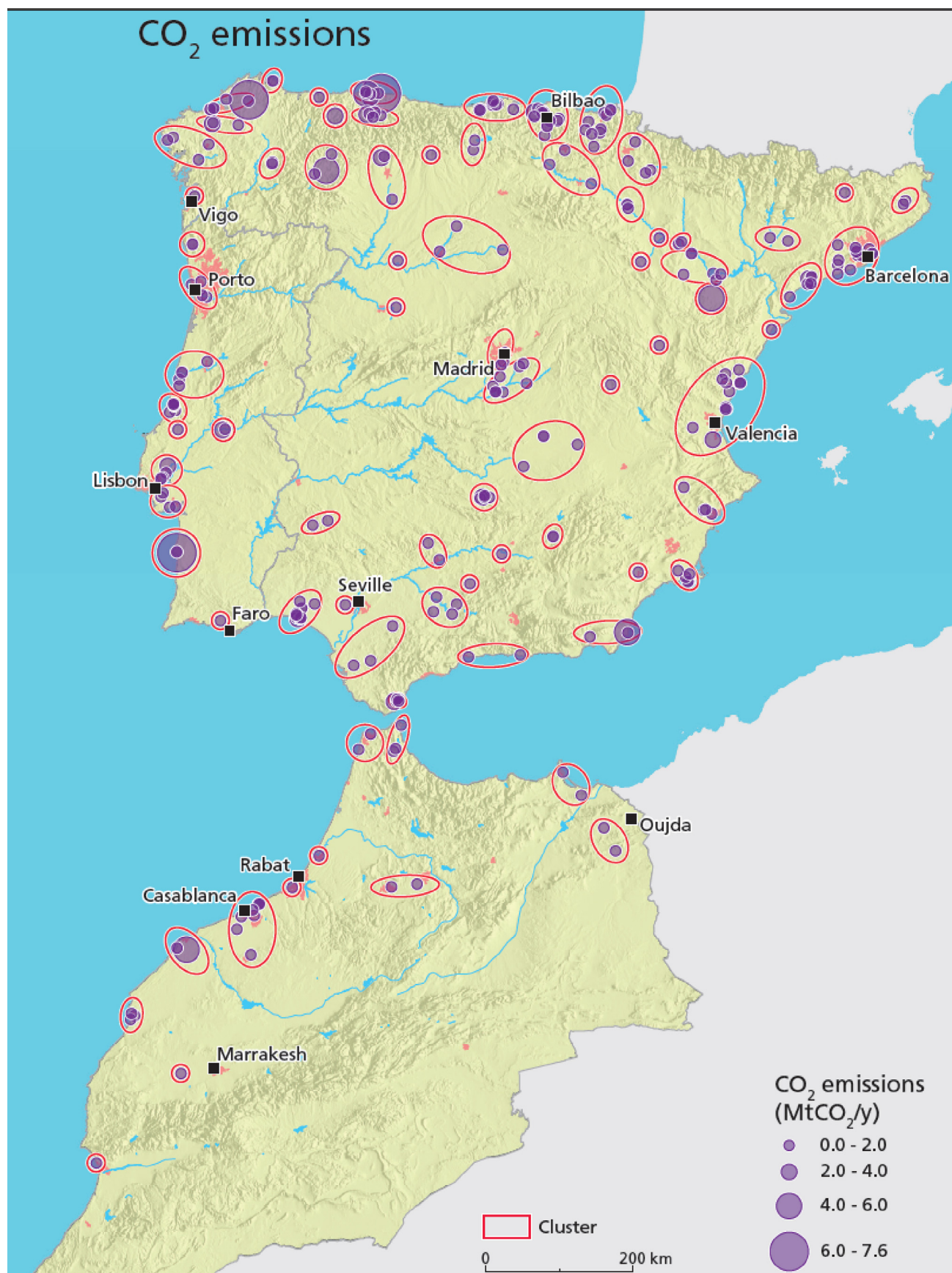


Fig. A1. A Location of CO₂ point sources and mean annual CO₂ emissions over the period 2005–2009. The transparent ovals and circles indicate the clusters of CO₂ point sources used for the modelling exercise.

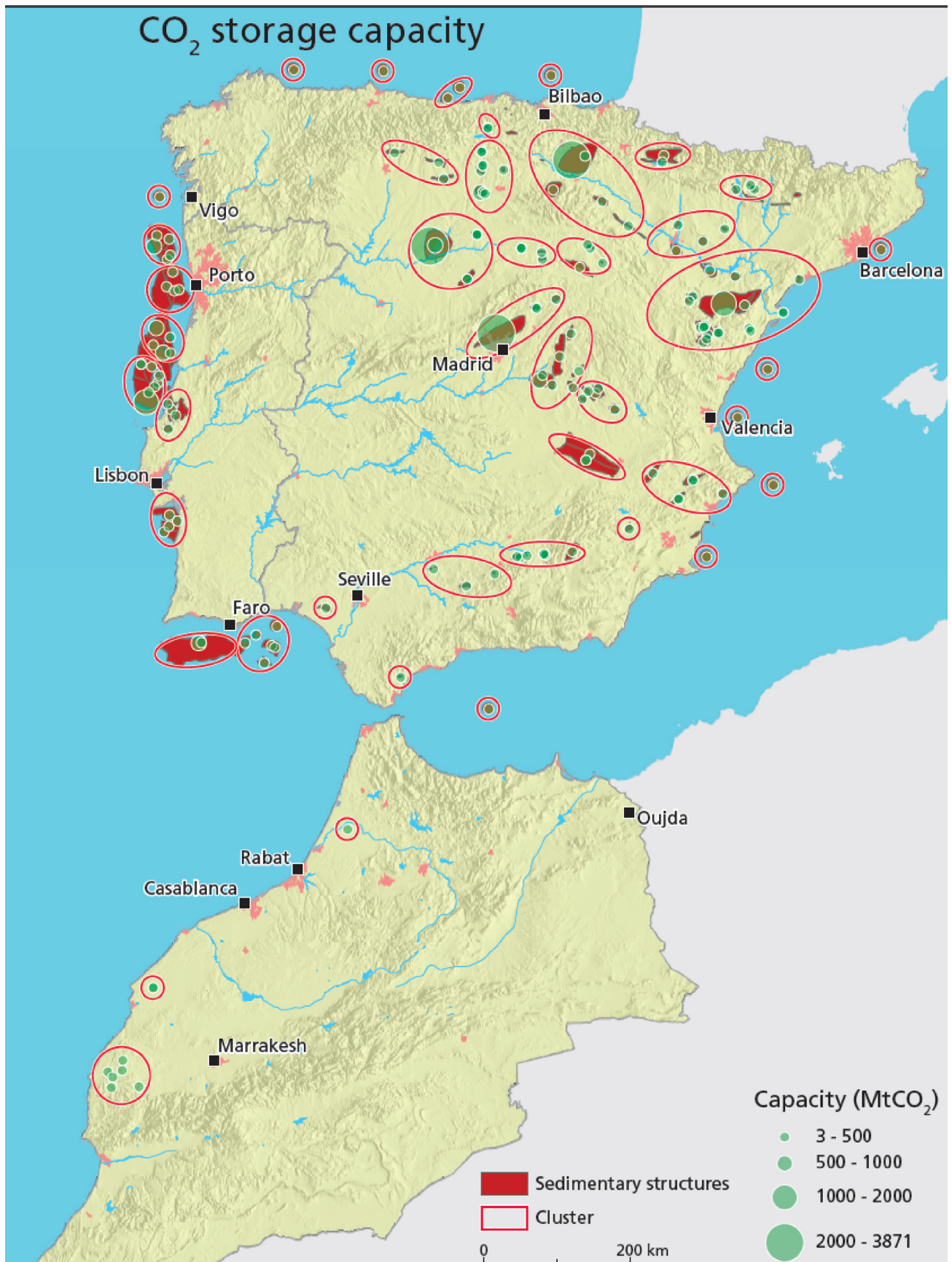


Fig. A2. Location of potential injection sites and storage capacity. Storage structures with a capacity less than 3 MtCO₂ are not shown. The transparent ovals and circles indicate the clusters of sinks used for the modelling exercise.

Table A1

Key characteristics of CO₂ point sources, CO₂ storage potential and CCS in the COMET model in the West Mediterranean for the years 2005–2009 and 2030 in the Conservative CCS, Cross-frontier and Free-routes scenarios.

	Spain	Portugal	Morocco
General			
CO ₂ point sources ^a (nr.)	221	35	29
Point source clusters ^b (nr.)	44	10	12
Storage structures ^c (nr.)	118	36	9
Storage potential ^c (GtCO ₂)	22	7.5	0.4
Storage clusters ^b (nr.)	28	8	4
2005–2009			
CO ₂ emissions ^a (MtCO ₂ /y)	153	28	28
2030			
CO ₂ emissions w/o capture (MtCO ₂ /y)	365	51	86
CO ₂ captured ^d (MtCO ₂ /y)	50	5	3
CO ₂ emissions after capture (MtCO ₂ /y)	327	47	84
CO ₂ avoided via CCS (MtCO ₂ /y)	38	4	3

^a Point sources emitting less than 0.08 MtCO₂/y were excluded from the inventory (Boavida and Sardinha, 2012; Boavida et al., 2012a; Martínez and Carneiro, 2011).^b The clustering of point sources and sinks was based on a case-by-case analysis rather than on an automated procedure imposing strict constraints (e.g. maximum CO₂ emission size or constant distances between point sources). Nevertheless, three criteria were followed loosely for identifying source clusters: (i) distance between point sources; (ii) least cost paths direction between point sources and sinks/sink clusters; and (iii) geographical and infrastructure barriers between point sources. Similarly, three criteria were used for the definition of sink clusters: (i) continuity of the geological basin/structure; (ii) distance between sinks and injection sites; and (iii) distinction between on-/offshore clusters. Both the point source and sink clusters show a considerable range in terms of size (point sources: 0.1–13.4 MtCO₂/y; sinks: 4–4, 312 MtCO₂) and number (point sources: 1–15; sinks: 1–20) (Mesquita et al., 2013).^c Storage structures with a capacity lower than 3 MtCO₂ were excluded from the inventory (Martínez and Carneiro, 2011).^d For 2030, the COMET model projects CO₂ capture to occur only in the power sector (both gas and coal-fired power plants) due to the relatively low CO₂ capture costs. A CO₂ capture rate of 90% was assumed for the electricity sector. CO₂ capture from industrial point sources (mainly in the cement sector in Spain and Portugal) was projected to occur after 2030 (Van den Broek et al., 2013).

The DBS identified in the literature review and country analyses were assessed for the CO₂ pipeline networks simulated for these three scenarios. The assessment was done for the CO₂ pipeline networks in the year 2030 (instead of 2050) as this will result in a lower uncertainty in the scenario parameters, pipeline networks configurations, and thus, route specific DBS.

Table A1 gives an overview of the key characteristics of the CO₂ sources, storage potential and CCS for the three scenarios in the WMR for the years 2005–2009 and 2030. Figs. 2–4 in Section 3 show the CO₂ pipeline networks for the Conservative CCS, Cross-frontier and Free-routes scenarios for the year 2030, respectively.

As can be seen in Figs. 2 and 3, the CO₂ pipeline networks in the Conservative CCS and Cross-frontier scenarios in 2030 are rather similar; this is mainly because in both scenarios the CO₂ pipelines have to follow the existing natural gas pipeline network. The key differences are the transboundary pipelines in the Cross-frontier scenario: between Vigo (north of Spain) and Porto (north of Portugal), between Abrantes (center of Portugal) and Córdoba (southwest Spain), and between Algeciras (south of Spain) and Ceuta/Tetouan (north of Morocco). Nevertheless, transboundary transport seems to play a limited role in the future CO₂ pipeline networks. Another notable difference is the pipeline network along the Moroccan coast, which emerges in the northwest in the Cross-frontier scenario as a result of the opportunity to store Moroccan CO₂ in low-cost Spanish storage reservoirs, instead of in the west of Morocco where storage sites are more expensive. The Free-routes scenario shows significantly more differences compared to the other two scenarios, mainly due to the freedom in pipeline routing, which resulted in more direct CO₂ pipeline connections,

especially in Spain. Also, whereas the Free-routes scenario shows three separate pipeline networks within Spain, the Conservative CCS and Cross-frontier scenario display a more integrated network within the country.

Figs. 2–4 show merely one offshore pipeline (Algeciras-Ceuta/Tetouan), which is used for transboundary transport in the Cross-frontier scenario (Fig. 3) rather than for offshore storage. In 2030, the backbone of the CO₂ pipeline network across the region is already in place and has a length of around 5.5×10^3 km in all three scenarios (compared to around 7.9×10^3 km in 2050) (Van den Broek et al., 2013a). Therefore, most of the investments in trunk pipelines will be needed in the period up to 2030. In the Conservative CCS scenario, pipeline investments amount up to 3.9 billion euro out of 4.6 billion in 2050. The Free-routes scenario shows that investments cost (0.6 billion euro in 2020) may be significantly lower compared to the Conservative CCS scenario (1.4 billion euro in 2020) while being able to store the same amount of CO₂, owing to the high degree of freedom in selecting pipeline routes. Investment cost could be substantially reduced (around 0.9 billion euro) by postponing a number of pipelines which are oversized for the period after 2030 (Van den Broek et al., 2013a).

Appendix B.

Table B1 gives an overview of the main technical features of the study of analogue pipeline trajectories used for this study. More detailed information on technical, legal, financial and organizational aspects can be found in COMET (2012a,b,c) as well as in the references presented in Table B1.

Table B1
Overview of main technical features of the analogue pipeline trajectories used for this study.

	Sines–Setubal	Sines–Aveiras de Cima	Setubal–Braga	Braga–Tuy	Leiria–Campo Maior	MEDGAZ	Compostilla
Sources	Hidroprojecto (2001)	Agripo Ambiente (1995)	SEIA (1995a,b, 1994)	IMPACTE (1997, 1996)	REN (2007)	Mikunda et al. (2011b)	Compostilla Project (2013)
Transported matter	Natural gas	Refined oil products	Natural gas	Natural gas	Natural gas	Natural gas	CO ₂
On-/offshore Route	Onshore Sines–Setubal	Onshore Sines–Aveiras	Onshore Setubal–Braga	Onshore Braga–Tuy	Onshore Campo Maior–Leiria	On- and offshore Beni Saf (Algeria)–Almeria (Spain)	Onshore Compostilla–Santa María del Monte de Cea
Transboundary	No	No	No	Yes	No	Yes	No
Project start	Not indicated	1996	Not indicated	1997	Not indicated	2006	Not finished yet ^a
Start year operation	2003	1996	1997	1997	1997	2008	Not finished yet ^a
Length pipeline (km)	87	147	580	76	220	210	140
Diameter pipeline (inch)	32	16	Apr-28	20	28	24	14
Capacity (10 ⁹ m ³ /yr)	6	0.2	3.7	0.6	3.7	8	0.001
Operating pressure (bar)	84	99	36–85	36–85	36–85	81	180
Materials pipeline	CS API 5L X70	CS API 5L Grx65	CS API 5L X70	CS API 5L X70	CS API 5L X70	Welded steel	CS API 5L Grx65
Coating	Not indicated	Not indicated	PE	PE	PE	PP anti-corrosion ^b	PE
Crossed terrains	Industrial, forest, agricultural, populated	Industrial, forest, agricultural, populated	Flat, agricultural, forestry, populated	Agricultural, industrial, forestry, populated	a.o. crop fields and pasture	Not indicated	Sandstone, slate, clay, marl
Follows other tracks	Yes (65 km)	Yes	No	No	No	No	Yes, for 17 km
River crossings	Yes	Yes	Yes	Yes	Not indicated	Yes (2)	Yes
Road crossings	Yes	Yes	Yes	Yes	Not indicated	Yes (18)	Yes
Railways	Yes	Yes	Yes	Yes	Not indicated	No	Yes
Monitoring system	Supervision/control centres; inspections by foot (each 3 months) and by helicopter (each 6 months)	System remote control from control centre; volume measuring + leak detection system; surveillance by foot and helicopter; PIGs ^c	System for supervision + control transport network; aerial, car and foot patrol are regularly carried out; PIGs ^c	Control system; surveillance pipeline; cathodic protection; optical cable along pipeline for information	Border station that monitors gas imports	Yes	Not indicated
Technical difficulties with construction	Crossing protected areas; 5 m. distance between pipeline axes required when crossing rivers or lakes	Crossing protected areas (Sado river); establishment ROW; risks related to infrastructure building	Crossing obstacles; digging restrictions; minimum distances from constructions and vegetation	Crossings protected areas + water bodies; use explosions in rocky areas; impact on environment	Not indicated	Changes in topography, crossing natural parks and other protected areas	Not indicated
Technical difficulties with operation	Not indicated	Not indicated	Compression, maintenance, monitoring, corrosion, pressure drops, intermittency	Not indicated	Not indicated	Onshore patrolling of route difficult in areas with low accessibility	Not indicated

^a By the end of 2013, it was decided not to proceed the Compostilla project to the full scale demonstration stage ([Foster Wheeler, 2013](#); [GCCSI, 2014](#)).^bThe parts of the pipeline nearest to the shores, down to depths of 250 m will also have an outside coating of reinforced concrete to provide stability and extra protection.^cPipeline Inspection Gauge (PIG).

Table C1

Stakeholders present at workshops in Spain, Portugal and Morocco.

Spain	Portugal	Morocco
ENDESA (energy company) ENAGÁS (natural gas company)	REN—Gasodutos S.A. (energy company) Galp Energia S.A. (natural gas company)	SAMIR (refinery company) CNRST (National center for scientific research and technology)
Gas Natural Fenosa (energy company)	ENDESA (Spanish energy company)	OREDDE (regional observatory for environmental and sustainable development of the East) National Moroccan phosphate company
Iberdrola (energy company)	EDP (Energy production management corporation) Tejo Energía, S.A. (energy company) CIMPOR (cement producer)	GPower Consultants ADEREE (Agency for the development of renewable energy and energy efficiency) Managem (mining and hydro metallurgy group) National office of electricity
UNESA (Spanish Association of the Power Industry)	DGEG (Directorate-General for Energy and Geology)	ONHYM (Moroccan Office of Hydrocarbons and Mining) Transcarbon (consultant)
Spanish CO ₂ platform	CECAC (Executive Committee of the Climate Change Commission)	
CEOE (Commission of Energy in the Spanish Confederation of Employers' Organizations) OECC (Spanish Office of Climate Change)	QUERCUS (National Association for Nature Conservation) DGPM (Directorate-General for regional policies)	
Oil and Gas Capital (Hydrocarbons' Prospecting company) ISOLUX CORSAN, S.A. (Global benchmark in the areas of concessions energy, construction and industrial services) IPF (Petrophysical Institute Foundation)	Royal Norwegian Embassy LNEG (National laboratory of energy and geology) FFCT (New University of Lisbon—Faculty of Science and Technology) UEVORA (University of Évora)	Ministry of energy, mines and water Ministry of Environment University Al Akhawayn
CIUDEN (Energy City Foundation) Air Liquide (industrial gas producer) CIEMAT (Spanish National Research Centre for Energy, Environment and Technology) IIMAC (Climate Change, Environmental and Energy Consulting company) IGME (Spanish institute for geology & mining) Ministry of Industry, Energy and Tourism		University of Rabat University of Mohammed 1st

Appendix C.

Table C1 gives an overview of the (local) stakeholders who attended the workshops in Spain, Portugal and Morocco.

Table C1 (Foster Wheeler, 2013; GCCSI, 2014).

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