Modeling CO_2 pipeline systems: An analytical lens for CCS regulation

Workshop - The Economics of Gas

A. Nicolle, D. Cebreros, O. Massol, E. Jagu Schippers

Industrial Engineering Research Department
Climate Economics Chair

May 22nd 2023

Laboratoire Génie Industriel

CEC Dauphine Université Paris | PSL

What is CCS?

CCS: **C**arbon **C**apture and **S**torage

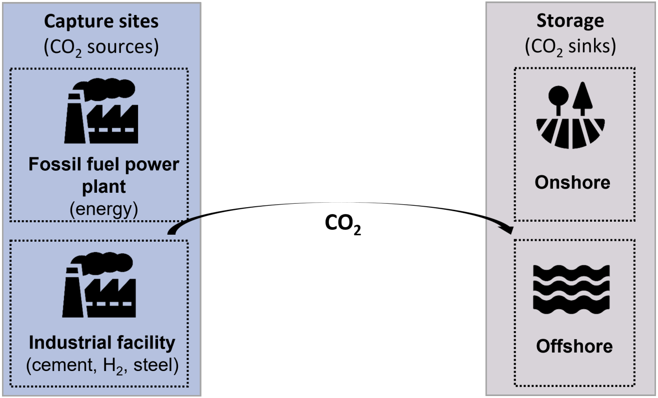

Figure 1: A first representation of CCS

What is CCS?

CCS: Carbon Capture, **Transportation** and Storage

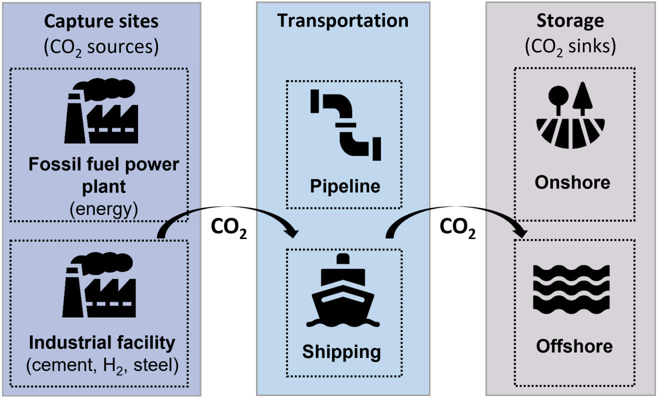

Figure 2: A better representation of CCS

High hopes...

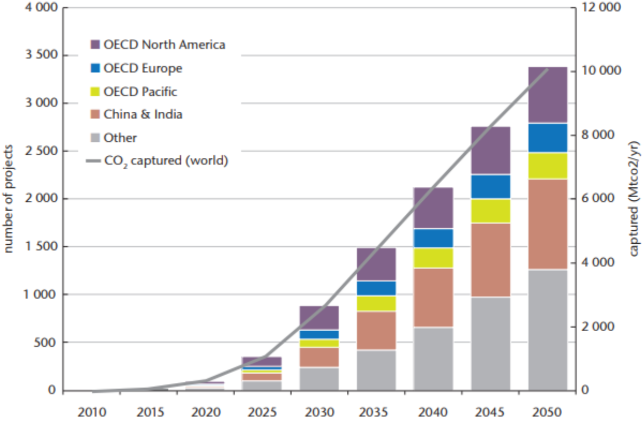

Figure 3: IEA "Blue Map" Scenario (IEA, 2009)

High hopes...

The IEA "Blue Map" scenario:

→ without CCS, overall costs increase by 70%

→ 300 MtCO_2 captured per year by 2020

Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) :

→ CCS expected to represent up to 55% of the CO_2 mitigation actions needed

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= Ambitious CCS growth path scenarios in the early 2000s

...and disillusionment

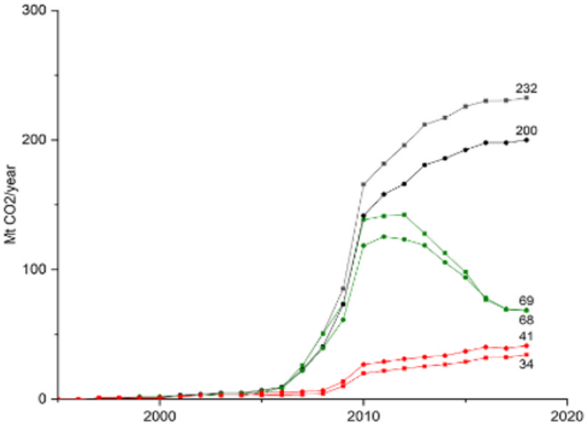

Figure 4: CCS capture and storage projects' capacity (Wang et al., 2021)
In black: planned capacity. In green: projects under construction & in operation. In red: projects in operation

A fresh momentum

The Inflation Reduction Act in the US (2022):

→ increase of the 45Q Carbon Capture tax credit

The Net Zero Industry Act in the EU (2023):

→ An EU storage target: 50 MtCO_2/y by 2030

→ Recognition of a need for coordination

→ Accelerated storage permitting procedures

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Are fixing new storage targets and closing the capture financial gap enough for deploying CCS on a large scale?

A main barrier: CCS transportation

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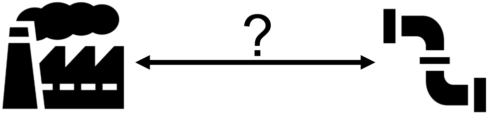
> *Stakeholders to a large extent underestimated transport and storage. [...] Transport was the most neglected component.*
>
> – von Hirschhausen et al., 2012

Among other barriers to large-scale deployment, CCS transportation has received scarce attention.

Chicken & egg problem

CCS transportation is a common **"Chicken & Egg"** problem (Herzog, 2011).



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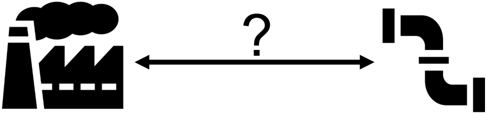

For the pipeline operator:

→ As a **natural monopoly**, it is prone to regulatory oversight
→ needs to be ensured that it can recoup its costs

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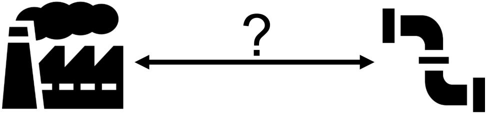

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→ subject to monopoly pricing

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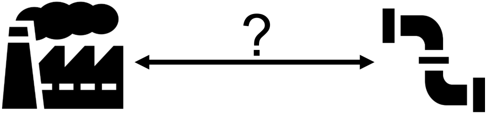

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Absent any regulatory signal, neither emitters nor pipeline operator will engage in CCS deployment

Current regulation: fuzziness prevails

	UK	U.S. Interstate	U.S. Intrastate	Norway	EU
Regulatory agency for rates and access	Ofgem likely to be appointed (BEIS 2022a)	Unclear regulatory mandate for pipelines crossing some federal lands and for pipelines not crossing federal lands	No agency, except for common carriers in Texas and Colorado	No agency, but the state intervenes as a project leader and as a stakeholder of the transportation infrastructure (Gassnova SF 2022)	Silent legislation
Non-discriminatory access prices	Yes	Mandatory for common carriers	Generally mandatory for common carriers	Yes (informational discussion)	Yes
Pricing scheme	Rate-of-return regulation combined with performance incentives (BEIS 2022a)	Project-dependent (STB intervenes in case of a dispute, see discussion in Appendix A)	Project-dependent	Two-tariff structure: (i) a user-specific maritime component based on distance, and (ii) a non-discriminatory access charge to the Norwegian onshore receiving terminal, the offshore pipeline, and the storage site	Silent regulation

Research question

Research question:
⇒ How does regulation affect social welfare of CCS pipeline transportation?

Scope of this presentation:

1. Discuss CO_2 pipeline transportation in the literature
2. Determine an engineering-based Cobb-Douglas production function
3. Provide insights into the impact of economic regulation of these infrastructures

Economic literature

Network optimization models

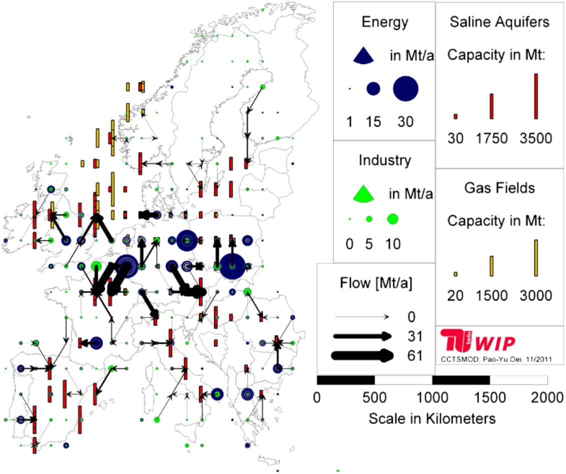

Figure 5: Source: Oei et al., 2014

Economic literature

A simplified CO_2 pipeline representation:

Table 3 Investment cost by pipeline diameter and respective annual transport capacity

Diameter (m)	Annual transport capacity (mio tCO_2 / a)	Investment costs (€ per tCO_2 and km)
0.2	6	0.29
0.4	18	0.19
0.8	71	0.10
1.2	174	0.06
1.6	338	0.04

Figure 6: Source: Oei et al., 2014

⇒ Economic models use a linear representation with discrete pipeline diameters that exhibit economies of scale.

Economic literature

From this overview, economic models tend to:

→ ignore the natural monopolistic character of the pipeline operator

→ rely on a simplified representation of a CO_2 cost function

→ use natural gas cost data for their cost functions, although acknowledging that their transportation's cost differ (Knoope et al., 2013).

Engineering literature

Numerical site-specific representation

$$D_i = \left\{ \frac{-64 Z_{ave}^2 R^2 T_{ave}^2 f_F \dot{m}^2 L}{\pi^2 \left[M Z_{ave} R T_{ave} \left(p_2^2 - p_1^2 \right) + 2 g P_{ave}^2 M^2 (h_2 - h_1) \right]} \right\}^{1/5}$$

$$\frac{1}{2\sqrt{f_F}} = -2.0 \log \left\{ \frac{\varepsilon / D_i}{3.7} - \frac{5.02}{\mathrm{Re}} \log \left[\frac{\varepsilon / D_i}{3.7} - \frac{5.02}{\mathrm{Re}} \log \left(\frac{\varepsilon / D_i}{3.7} + \frac{13}{\mathrm{Re}} \right) \right] \right\}$$

Figure 7: Source: McCoy, 2008

⇒ Specific equations that do not allow an economic analysis

Wrap-up

Overall:

- → Economic models tend to oversimplify the CO_2 pipeline equations
- → Engineering models are generally site-specific and hard to compute

⇒ There is a need to build an analytical cost function to inform regulatory debates

System Definition

System under consideration:

Trunk pipeline + Pumping station

- → Point-to-point pipeline of length L and output Q
- → Constant elevation, no bends
- → CO_2 transported in a dense phase state
- → Onshore or offshore
- → possibly an "elementary module"

Engineering-based production function

Flow equation (Vandeginste & Piessens, 2008):

$$D = \frac{4^{10/3} n^2 Q^2 L \rho g}{\pi^2 \rho^2 \Delta P}^{3/16} \tag{1}$$

with n the Manning factor, g the gravity constant, ΔP the pressure drop.

Pumping power (Mohitpour et al., 2003):

$$W_p = \frac{Q \Delta P}{\rho \eta_p} \tag{2}$$

with η_p the efficiency of the pump and ρ density of CO_2.

Engineering-based production function

After simplification:

$$Q^{\beta} = K^{\alpha} E^{1-\alpha} \tag{3}$$

with K the capital, E the energy, $\beta = 9/11$ and $\alpha = 8/11$
$\beta < 1$

- $\rightarrow$ The system exhibits economies of scale
- $\rightarrow$ verifies technical condition for a natural monopoly (Sharkey, 1982)

Regulatory scenarios

We now introduce a demand function $P(Q) = AQ^{-\epsilon}$

Cases	Optimization problems
Marginal cost-pricing (*)	$\max_Q W(Q) = \int_0^Q P(q)dq - C(Q)$
Unregulated private monopoly (M)	$\max_Q \Pi(Q) = P(Q)Q - C(Q)$
Average cost-pricing solution (avg)	$\max_Q W(Q) = \int_0^Q P(q)dq - C(Q)$ $s.t\ \Pi \geq 0$

with Π the profit of the pipeline operator

Results

	$\frac{1}{\epsilon}$				
	1.13	1.19	1.25	1.31	1.38
Output					
$\frac{Q^M}{Q^*}$	0.046	0.062	0.074	0.084	0.093
$\frac{Q^{\text{avg}}}{Q^*}$	0.752	0.737	0.723	0.708	0.691
Capital					
$\frac{K^M}{K^*}$	0.081	0.102	0.119	0.132	0.143
$\frac{K^{\text{avg}}}{K^*}$	0.792	0.779	0.767	0.754	0.739
Welfare					
$\frac{W(Q^M)}{W(Q^*)}$	0.804	0.772	0.748	0.729	0.711
$\frac{W(Q^{\text{avg}})}{W(Q^*)}$	0.996	0.995	0.992	0.990	0.987

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Conclusion

→ Economic regulation is still in early stage but it is necessary to establish the rules now

→ We have proved analytically that the CO_2 pipeline system exhibits economies of scale and verifies the technical condition for a natural monopoly

→ the Cobb Douglas-Douglas production function is a first analytical tool for policymakers

→ We find an efficiency gap between economic and environmental objectives

Thank you for your attention!

Questions/comments?

adrien.nicolle@chaireeconomieduclimat.org

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