The thesis defense is going to start

Boulevard of broken dreams? The economics of CCS transportation

Ph.D. Defense by Adrien Nicolle

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ÉCOLE DOCTORALE Interfaces: matériaux, systèmes, usages

CEC Dauphine | PSL

December 18th 2024

General introduction - Context

What's CCS? **C**arbon **C**apture and **S**torage

Capture sites

(fossil fuel power plant, cement producer, H2, steel producer, ...)

Storage

(onshore, offshore)

General introduction - Context

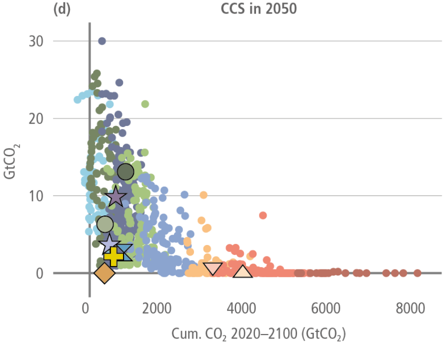
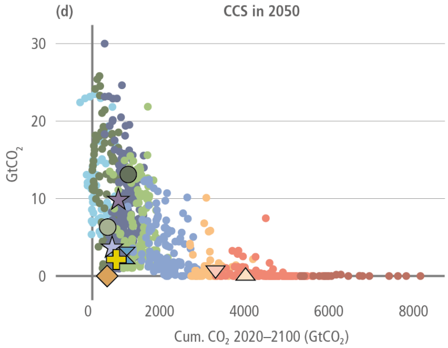


Figure 1: CCS capacity in 2050 as a function of cumulative emissions (IPCC, 2022)

General introduction - Context



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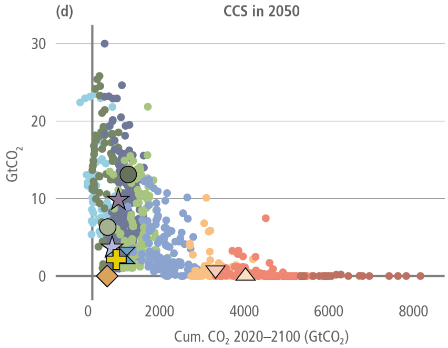

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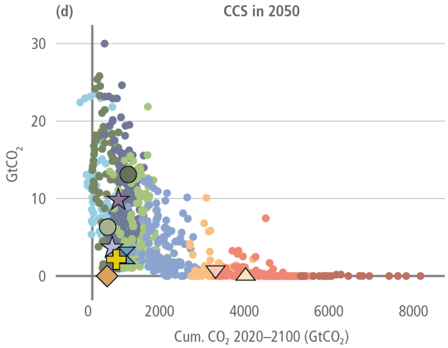

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Mitigation pathways that limit warming to 1.5°C and 2°C involve CCS on a large scale

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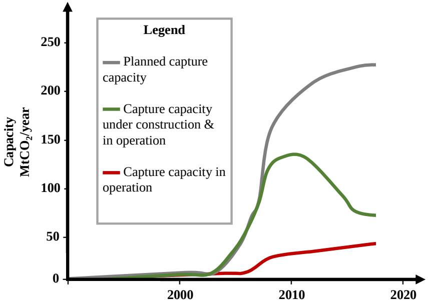

Figure 2: Global CO_2 capture capacity over time. Adapted from (N. Wang et al., 2021).

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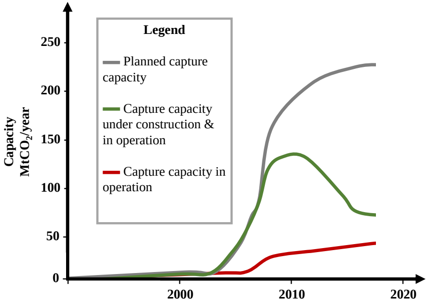

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→ Capacity in operation is **far from objectives**

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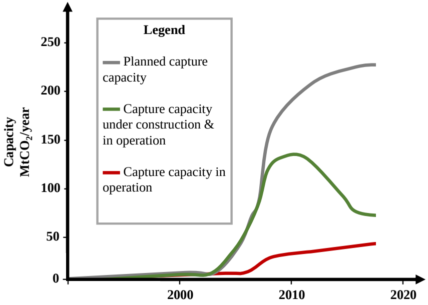

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→ **Discrepancy** between planned capacity and capacity in operation

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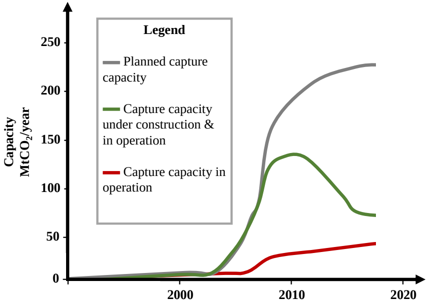

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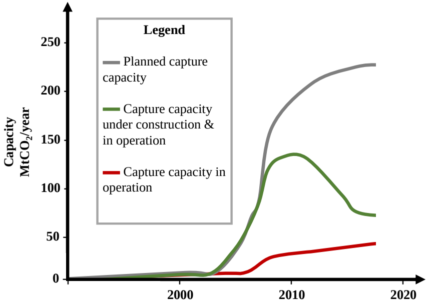

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*"Currently, **global rates of CCS deployment are far below those in modelled pathways** limiting global warming to 1.5° C or 2° C."* (IPCC, 2022)

General Introduction - Context

Against this background, a **new momentum** for CCS deployment

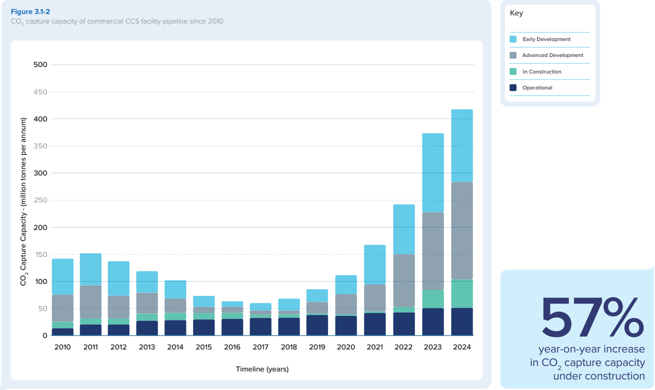

Figure 3: CO_2 capture capacity evolution since 2010

General Introduction - Context

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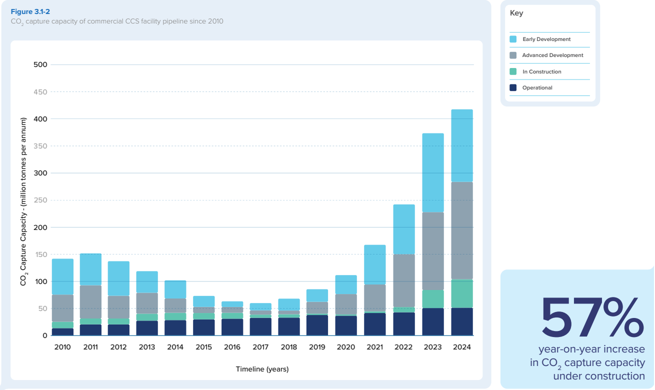

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Is it different this time?

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What's CCS? **C**arbon **C**apture, **Transportation**, and **S**torage

Capture sites

(fossil fuel power plant, cement producer, H2, steel producer, …)

Transportation

(pipelines, shipping, barges, trucks, …)

Storage

(onshore, offshore)

Shipping and **pipeline transportation** are the preferred options for **long-term deployment** (Oeuvray et al., 2024)

General introduction - Context

A need to study CCS transportation...

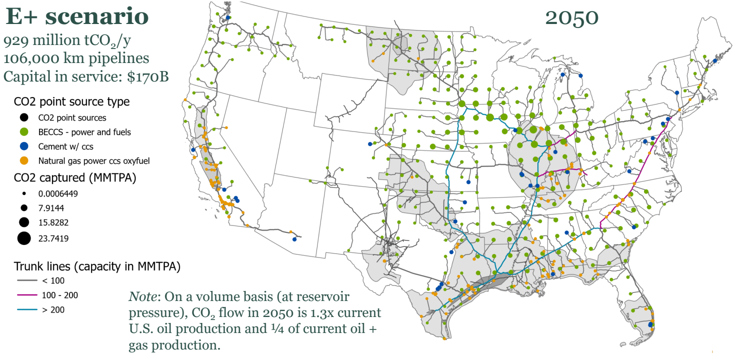

Figure 4: CCS deployment in the US: a national infrastructure (Larson et al., 2021)

General introduction - Context

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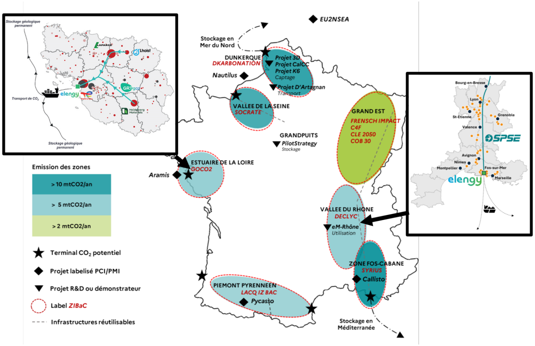

Figure 4: CCS deployment in France: a local cluster approach (CRE, 2024)

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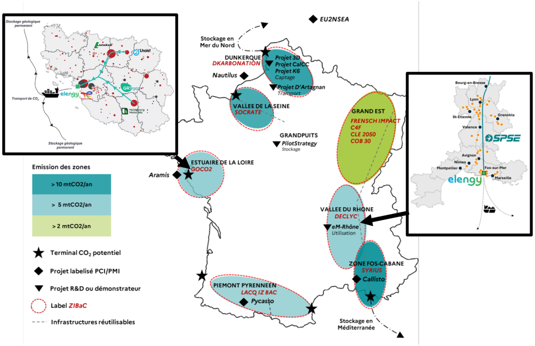

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... as it can hamper the feasibility of CCS (Herzog, 2011; Massol et al., 2015; Simonsen et al., 2024)

General Introduction - Context

Which challenges for CCS transportation?

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From a technical perspective:

→ **Pipelines** perform well in terms of cost, **economies of scale**, global warming impact, and reliability (Oeuvray et al., 2024)

→ **Dedicated ships** offer more **flexibility** and are useful for longer distances and smaller mass flows (Roussanaly et al., 2021)

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→ Shipping is a **contestable market** (Baumol et al., 1982)

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Shipping faces less economic challenges than pipeline deployment

General Introduction - Context

Which challenges for CCS *pipeline* transportation?

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Which challenges for CCS *pipeline* transportation?

1. Regulation

Figure 5: Report by la CRE on CCS transportation regulation (Sep. 2024)

General Introduction - Context

Which challenges for CCS *pipeline* transportation?

1. Regulation
2. Right-sizing the gathering pipeline system

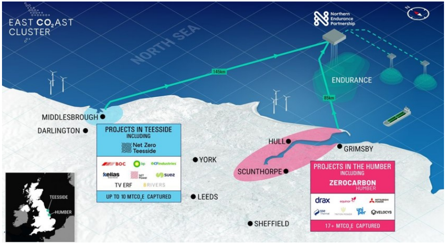

Figure 5: East Coast Cluster diagram

General Introduction - Context

Which challenges for CCS *pipeline* transportation?

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2. Right-sizing the gathering pipeline system
3. Chicken & Egg problem

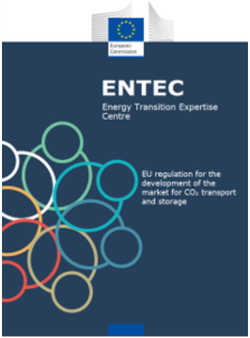

Figure 5: Report emphasizing the *'chicken-and-egg'* problem (2023)

General Introduction - Context

Which challenges for CCS *pipeline* transportation?

1. Regulation
2. Right-sizing the gathering pipeline system
3. Chicken & Egg problem
4. International cooperation

Figure 5: Integrating CCS in international cooperation (2023)

General introduction - Outline

This thesis develops four chapters dealing with the transportation stage of CCS

1. Chapter 1: Regulation of CCS transportation
2. Chapter 2: Oversizing CCS pipeline systems under uncertainty
3. Chapter 3: Kickstarting CCS adoption through subsidies
4. Chapter 4: CCS deployment in India
5. General Conclusion

Chapter 1 - Presentation

Chapter 1
Regulation of CCS transportation

This chapter has been published in **Economics of Energy & Environmental Policy**: Nicolle, A., Cebreros, D., Massol, O., & Jagu Schippers, E. (2023). Modeling CO_2 pipeline systems: An analytical lens for CCS regulation. *Economics of Energy & Environmental Policy* **12**(2). https://doi.org/10.5547/2160-5890.12.2.anic

Chapter 1 - Context and Background

Pipeline networks as natural monopolies: various forms of regulation

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Natural gas

→ long history of regulation (Natural Gas Act of 1938)
→ non-discriminatory tariffs
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→ "self-regulation"
→ alternative transport options created competitive pressures

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Where does CCS pipeline transportation stand ?

Chapter 1 - Context and Background

Why is the monopolistic nature an issue? (Klein et al., 1978)

→ **For the capture sites:** subject to monopoly pricing

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Chapter 1 - Context and Background

Why is the monopolistic nature an issue? (Klein et al., 1978)

→ **For the capture sites:** subject to monopoly pricing

→ **For the pipeline operator:** it is prone to regulatory oversight and needs to be ensured that it can recover its costs

→ **For the regulator:** there is a need to possess knowledge on the CCS cost function

Chapter 1 - Contributions

How does the regulation of CCS pipeline transportation impact social welfare?

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Literature review

→ **Context:** Natural monopoly? No quantitative assessment (Krahé et al., 2013; Roggenkamp and Haan-Kamminga, 2010)

→ **Methodology:** Existing cost functions are not adapted for regulatory economic assessments (Knoope et al., 2013; McCoy, 2008)

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Contributions

→ Analytical production function

→ Natural monopoly

→ Conflict between environmental and economic issues

Chapter 1 - Overview

An overview of existing regulatory practices:

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CCS regulation is either unclear or a reproduction of existing regulation

Chapter 1 - Methodology

Frontier-based benchmarking	Econometric estimation	Analytical production function
(Färe et al., 2013)	(Ellig and Giberson, 1993; Gordon et al., 2003; Oliver, 2015)	(Chenery, 1949, 1952; Perrotton and Massol, 2018)

Figure 6: Common regulatory approaches for approximating a cost function

Chapter 1 - Methodology

Frontier-based benchmarking
(Färe et al., 2013)

Econometric estimation
(Ellig and Giberson, 1993; Gordon et al., 2003; Oliver, 2015)

Analytical production function
(Chenery, 1949, 1952; Perrotton and Massol, 2018)

Figure 7: Common regulatory approaches for approximating a cost function

Ex-ante assessment requires to produce an analytical production function analysis

Chapter 1 - Methodology

System under consideration:

Trunk pipeline + Pumping station

Engineering-based equations (Chenery, 1949; Yépez, 2008):

→ Flow equation (Vandeginste and Piessens, 2008)

→ Pumping power equation (Mohitpour et al., 2003)

→ Mechanical equation (Ruan et al., 2009)

Chapter 1 - Methodology

Introduction of 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)	$\max_{Q} W(Q) = \int_0^Q P(q)dq - C(Q)$ $s.t. \Pi \geq 0$

Table 1: Three regulatory scenarios under non-discriminative prices

Chapter 1 - Results

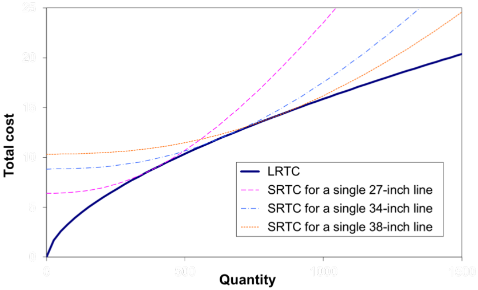


Figure 8: CO_2 pipeline system long-run total cost (LRTC) and short-run total cost (SRTC)

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

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

- $\rightarrow$ Economies of scale
- $\rightarrow$ **Natural monopoly** (Sharkey, 1982)

Chapter 1 - Results

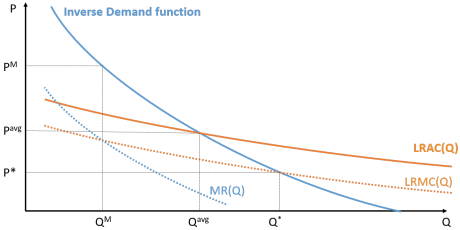
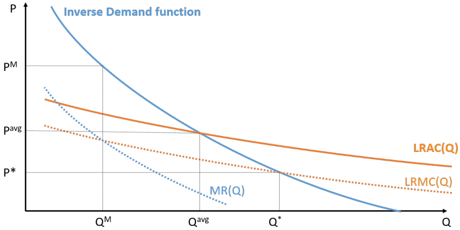


Figure 9: Results under the three regulatory scenarios

$\rightarrow \; W^M \approx 0.75 W^*$

Chapter 1 - Results



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$\rightarrow \quad W^M \approx 0.75 W^*$
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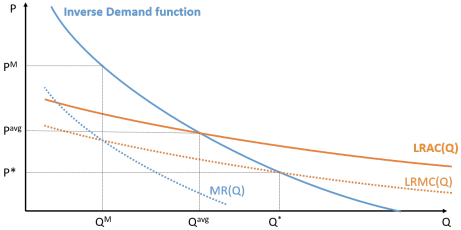

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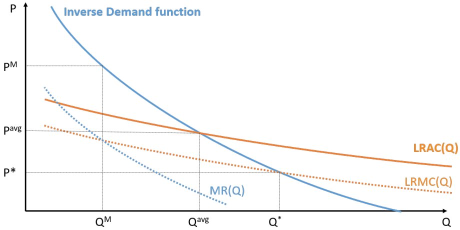
- $\rightarrow$ $W^M \approx 0.75 W^*$
- $\rightarrow$ $W^{avg} \approx 0.99 W^*$
- $\rightarrow$ But $Q^{avg} \approx 0.7 Q^*$ (as a generic result)

Chapter 1 - Results



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Conflicting objective between **environmental objective** (quantities) and **economic objective** (welfare)

Chapter 1 - Conclusion

How does the regulation of CCS pipeline transportation impact social welfare?

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Conclusions

- → The CO_2 pipeline system verifies the conditions for a natural monopoly
- → Average cost-pricing performs well in terms of welfare losses but conflicts with environmental objectives

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→ Average cost-pricing performs well in terms of welfare losses but conflicts with environmental objectives

Policy insights

→ This chapter highlights the need for dedicated regulation

→ It questions the use of non-discriminatory pricing

Chapter 2 - Presentation

Chapter 2

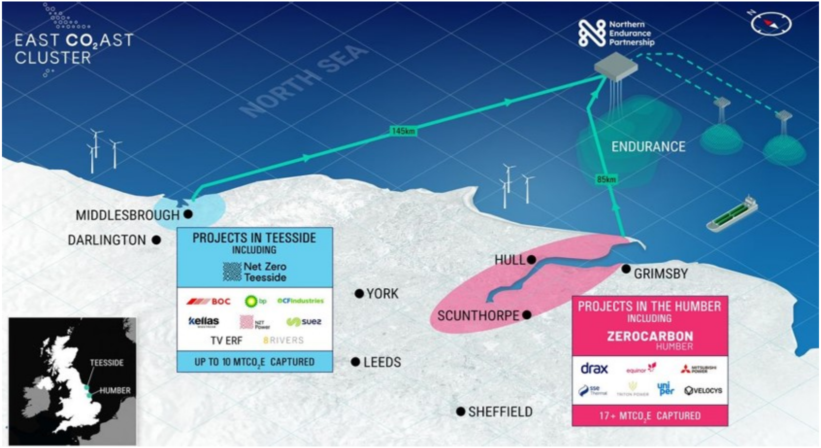
Oversizing CCS pipeline systems under uncertainty

This chapter has been published in **Energy Policy**:

Nicolle, A., & Massol, O. (2023). Build more and regret less: Oversizing H_2 and CCS pipeline systems under uncertainty. *Energy Policy* **179**, 113625.

https://doi.org/10.1016/j.enpol.2023.113625

Chapter 2 - Context and Background



Chapter 2 - Context and Background

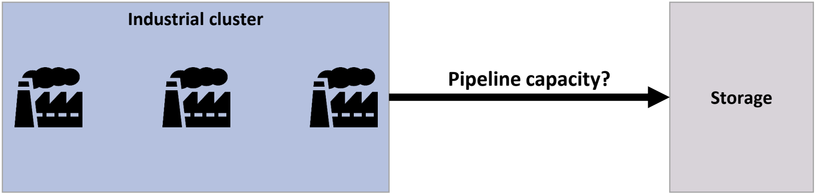


Figure 10: The pipeline operator's problem

→ Irreversible decision at the construction stage

→ Shared trunkline system

Chapter 2 - Context and Background

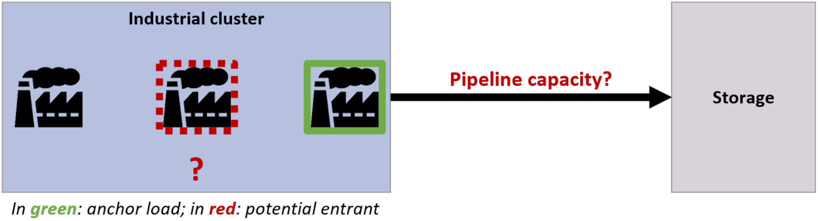
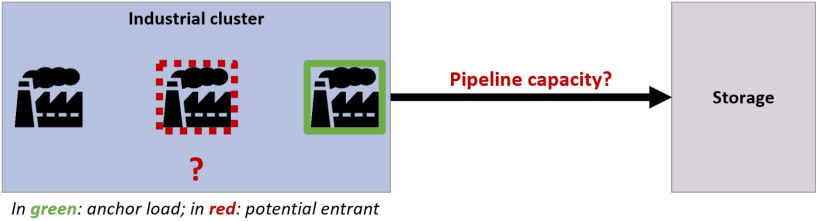


Figure 11: The pipeline operator's problem under uncertainty

In practice, the pipeline operator faces **uncertainty**

Chapter 2 - Context and Background



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In practice, the pipeline operator faces **uncertainty**

$\rightarrow$ Probability of new entrants?

$\rightarrow$ Minimize losses rather than maximize profits

Chapter 2 - Context and Background

$=$ While it may be cost-minimizing to oversize, the *uncertain* pipeline operator may not be willing to do so.

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$\rightarrow$ **Engineering economics**: A project planner that **oversizes** its infrastructure to lower intertemporal cost (Chenery, 1952)

Chapter 2 - Context and Background

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Should the regulator support oversizing?

$\rightarrow$ **Engineering economics**: A project planner that **oversizes** its infrastructure to lower intertemporal cost (Chenery, 1952)

$\rightarrow$ **Regulatory economics**: A project planner that **overcapitalizes** to exploit regulatory flaws (Averch and Johnson, 1962)

Chapter 2 - Contributions

How should the pipeline operator right-size the infrastructure under uncertainty?

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Literature review

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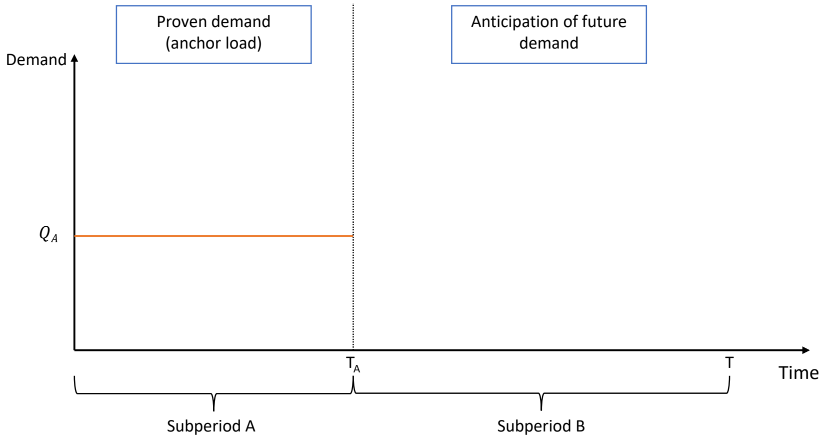
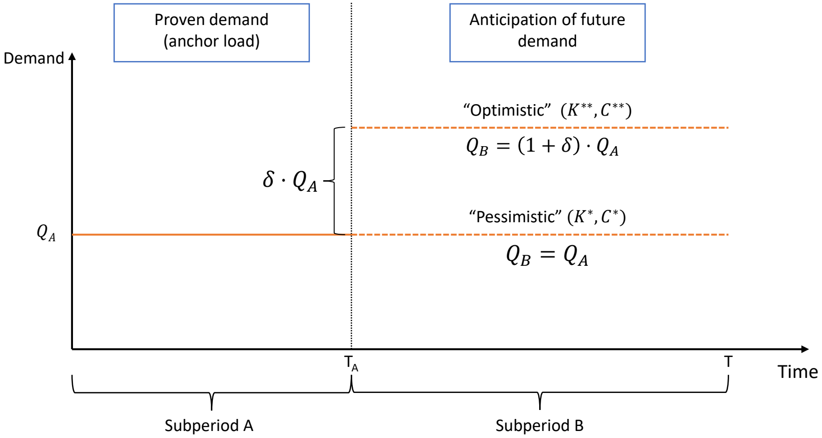
Contributions

→ Uncertainty of future demand
→ Building for the anchor load only is regret-maximizing
→ Regulatory tool

Chapter 2 - Methodology



Chapter 2 - Methodology



Chapter 2 - Methodology

Unknown probabilities + minimize losses: Minimax regret framework

Regret: the deviation from the decision that minimizes the costs for this scenario

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	The pipeline operator's decision	
	Pessimistic pipeline operator K^*	Optimistic pipeline operator K^{**}
Low demand scenario $\delta = 0$	0	$R(K^{**}, \delta = 0)$
High demand scenario $\delta > 0$	$R(K^*, \delta > 0)$	0
Max normalized regret	$R(K^*, \delta > 0)$	$R(K^{**}, \delta = 0)$

Table 2: A minimax regret approach (Savage, 1951)

Chapter 2 - Results

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Table 3: Results for two scenarios

Chapter 2 - Results

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Case study in the East Coast Cluster shows that **regret is divided by three** in the oversizing decision.

Chapter 2 - Results

	The pipeline operator's decision		
	K^*	K^{**}	K^{***}
Low demand $\delta = 0$	0	$R(K^{**}; 0)$	$R(K^{***}; 0)$
Mid demand δ_1	$R(K^*; \delta_1)$	0	$R(K^{***}; \delta_1)$
High demand δ_2	$R(K^*; \delta_2)$	$R(K^{**}; \delta_2)$	0
Max normalized regret	$\mathbf{R(K^*; \delta_2)}$	$\max\left(R(K^*; 0), R(K^*; \delta_2)\right)$	$R(K^{***}; 0)$

Table 4: Regret table for a three-case scenario

Chapter 2 - Conclusion

How should the pipeline operator right-size the infrastructure under uncertainty?

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Conclusions

→ Building for the proven demand maximizes regret

→ Case study shows that building ahead of demand divides regret by three

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Conclusions

- → Building for the proven demand maximizes regret
- → Case study shows that building ahead of demand divides regret by three

Policy insights

- → This chapter allows the regulator to distinguish an overcapitalizing behavior from a benevolent one
- → It supports an "infrastructure push"
- → It calls for appropriate contract developments due to the potential sunk costs that can arise

Chapter 3 - Presentation

Chapter 3

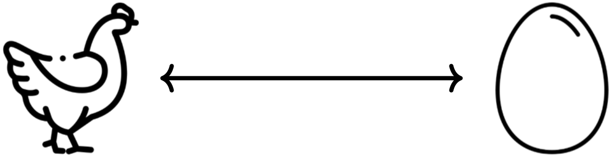
Kickstarting CCS adoption through subsidies

This chapter is under major revision in **Energy Economics**:

Nicolle, A., Lowing, D., & Cebreros, D. Kickstarting CCS adoption through subsidies.

Chapter 3 - Context and Background

CCS faces a **"Chicken & Egg"** problem (Herzog, 2011).



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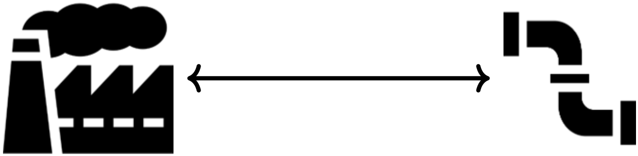

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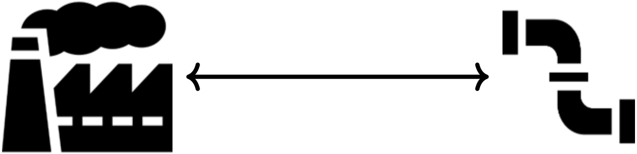

Emitter
Waits for T&S infrastructure before investing into carbon capture

Chapter 3 - Context and Background

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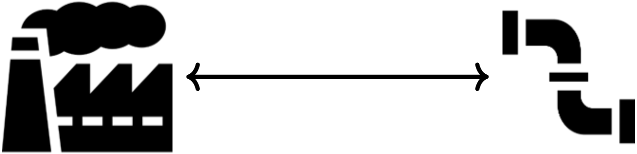

Emitter
Waits for T&S infrastructure before investing into carbon capture

T&S Operator
Waits for **critical mass of emitters** before investing

Chapter 3 - Context and Background

Problem: Heterogeneous emitters

Industrial sector	Carbon avoided cost [€/$tCO_{2,\text{avoided}}$]	Capture rate [-]
Ammonia	20	0.8
Cement	50	0.9
Steel	60	0.9
Pulp & paper	60	0.9
Refineries and petrochemicals	100	0.7

Table 5: Carbon capture avoidance cost by sector

Chapter 3 - Context and Background

Problem: Heterogeneous emitters

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Table 5: Carbon capture avoidance cost by sector

→ **Coordination failure** under similar economic incentive (e.g., EU-ETS)

Chapter 3 - Context and Background

Problem: Heterogeneous emitters

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Table 5: Carbon capture avoidance cost by sector

→ **Coordination failure** under similar economic incentive (e.g., EU-ETS)

The **Emitters' coordination problem** calls for public intervention in the form of **dedicated subsidies** (Sákovics and Steiner, 2012)

Chapter 3 - Contributions

How should CCS subsidies be distributed among emitters to kickstart CCS adoption?

Chapter 3 - Contributions

How should CCS subsidies be distributed among emitters to kickstart CCS adoption?

Literature review

- → **Context:** Heterogeneity of emitters + shared infrastructure + subsidy budget (Agaton, 2021; Banal-Estañol et al., 2016; Comello and Reichelstein, 2014)
- → Lack of coordination and heterogeneity considerations (Fattouh et al., 2024)

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Contributions

- → Subsidy distribution accounting for capture and transportation
- → Avoids strategic behaviour
- → Flexible

Chapter 3 - Methodology

Overview

Inputs

- $\rightarrow$ Subsidy budget $\mathcal{E}$.
- $\rightarrow$ Emitters N + capture costs $(x_i)_{i \in N}$.
- $\rightarrow$ Network P + transportation cost $(y_{iP(i)})_{i \in N}$.

Chapter 3 - Methodology

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1st step

- $\rightarrow$ **Objective**: Evaluation of emitters contribution to the network cost $||y||$.
- $\rightarrow$ **Approach**: Shapley value $\longrightarrow (Sh_i)_{i \in N}$.

$\leftarrow$ *Polynomial time.*
$\leftarrow$ *Core-stability.*

Chapter 3 - Methodology

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$$(c_i)_{i\in N} = (x_i)_{i\in N} + (Sh_i)_{i\in N}$$

2nd step

- $\rightarrow$ **Objective**: Subsidy distribution under budget constraint $\mathcal{E} \leq ||c||$.
- $\rightarrow$ **Approach**: Proportional solution $\longrightarrow (P_i)_{i\in N}$.

$\leftarrow$ *Non-manipulable.*
$\leftarrow$ *Claim-monotonic.*

Chapter 3 - Methodology

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Results

Final subsidy distribution.

Chapter 3 - Methodology

2^{nd} step – Claims problem

Objective: distribute subsidies based on emitter's claim

$$(c_i)_{i \in N} = (x_i)_{i \in N} + (Sh_i)_{i \in N}$$

Chapter 3 - Methodology

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Assumption: Subsidy budget < Total sum of claims

Chapter 3 - Methodology

2^{nd} step – Claims problem

Objective: distribute subsidies based on emitter's claim

$$(c_i)_{i \in N} = (x_i)_{i \in N} + (Sh_i)_{i \in N}$$

Assumption: Subsidy budget $<$ Total sum of claims

- → This defines a *"claims problem"* (O'Neill, 1982)
- → This chapter relies on Bankruptcy theory (Thomson, 2003)
  - » Many possible bankrupt solutions
  - » Need to select axioms relevant to our study

Chapter 3 - Methodology

2nd step – Axioms

Relevant axioms to CCS development:

Chapter 3 - Methodology

2^{nd} step – Axioms

Relevant axioms to CCS development:

1. **Claim monotonicity**: if an agent's claim increases, ceteris paribus, then they should receive at least as much as they did initially

Chapter 3 - Methodology

2nd step – Axioms

Relevant axioms to CCS development:

1. **Claim monotonicity**: if an agent's claim increases, ceteris paribus, then they should receive at least as much as they did initially
2. **Non-manipulability**: if a group of individual claimants merge into a single claimant, their resulting claim is the sum of the individual claims.

Chapter 3 - Methodology

2^{nd} step – Proportional solution

Theorem

A solution f on $\mathbb{B}$ is the P solution if and only if it satisfies Claim monotonicity and Non-manipulability (Moreno-Ternero, 2006).

Chapter 3 - Methodology

2^{nd} step – Proportional solution

Theorem

A solution f on $\mathbb{B}$ is the P solution if and only if it satisfies Claim monotonicity and Non-manipulability (Moreno-Ternero, 2006).

Definition

Consider any $(N, c, \mathcal{E}) \in \mathbb{B}$. The **Proportional** solution P is defined as

$$\forall i \in N, \quad P_i(N, c, E) = \frac{c_i}{\sum_{j \in N} c_j} \mathcal{E}.$$

Chapter 3 - Results

Model inputs

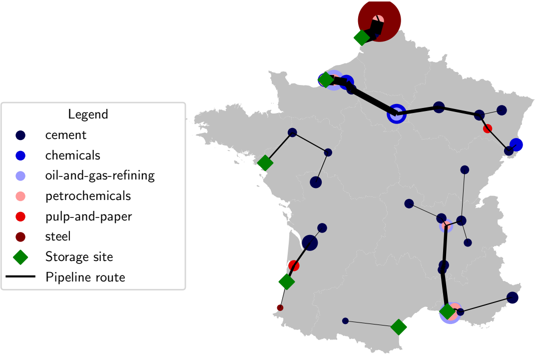

Figure 12: Emitters and network input
Size of dots are proportional to annual emissions. MILP

Chapter 3 - Results

Case study

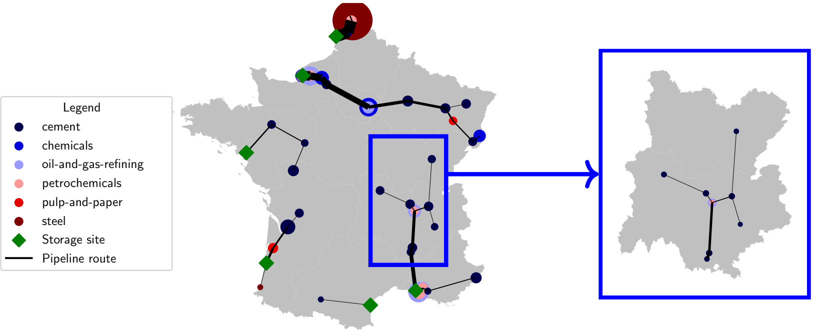

Figure 13: Focus on a small cluster

Chapter 3 - Results

1st step

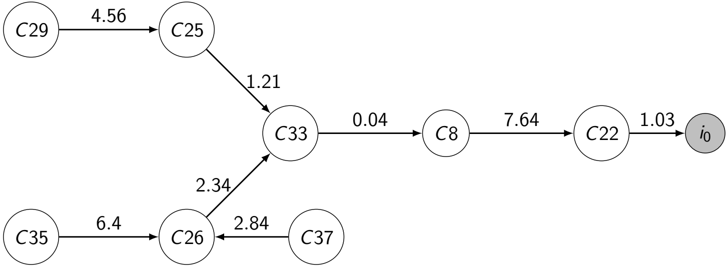

Figure 14: Network and pipelines' costs

$i \in N$	$C22$	$C8$	$C33$	$C25$	$C29$	$C26$	$C37$	$C35$
$Sh_i(N, v^P)$	0.128	1.219	1.226	1.831	6.391	2.006	4.846	8.406
c_i	20.305	61.769	22.736	20.271	21.831	20.186	15.596	21.536

Table 6: First step's results (in M€/y)

Chapter 3 - Results

2nd step results

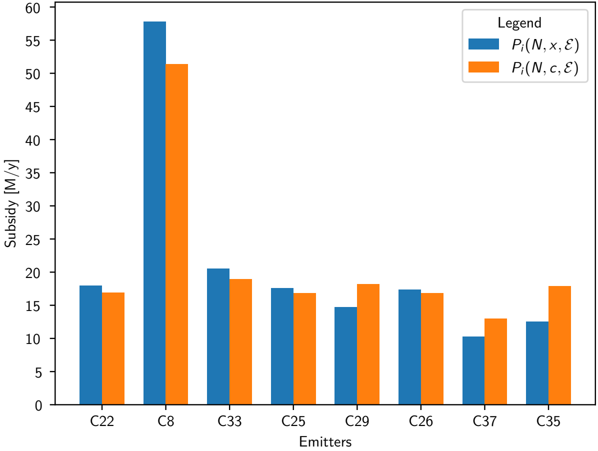

Figure 15: P results in base case $(N, c, \mathcal{E})$ and without considering the network $(N, x, \mathcal{E})$.

Chapter 3 - Results

2^{nd} step results

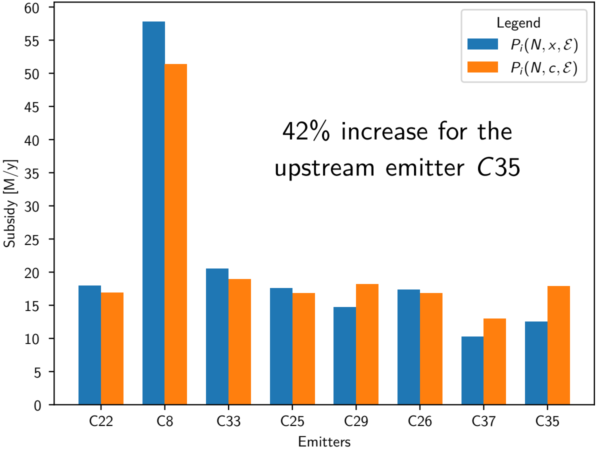

Figure 15: P results in base case $(N, c, \mathcal{E})$ and without considering the network $(N, x, \mathcal{E})$.

Chapter 3 - Conclusion

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Conclusions

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→ It finds that upstream emitters receive more subsidies

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Conclusions

- → This chapter develops a flexible methodology that formalizes the design of CCS subsidy mechanisms.
- → It finds that upstream emitters receive more subsidies

Policy insights

- → The subsidy distribution acknowledges emitters' heterogeneity
- → It avoids strategic behavior
- → It incorporates both transportation and capture stages of a CCS infrastructure.

Chapter 4 - Presentation

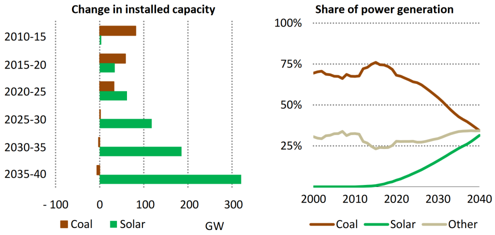
Chapter 4

CCS deployment in India

This chapter will be submitted to **Environmental Modeling & Assessment**:
Nicolle, A., Monjon, S, & Massol, O. Routing India towards Net Zero: Optimal planning of the CCS infrastructure.

Chapter 4 - Context and Background

Indian Power Sector: Committed to Net Zero by 2070?



Phasing-out of coal:

$\rightarrow$ $\approx$ 30 GW in 2020-2025

$\rightarrow$ $\approx$ 0 GW in 2025-2030

Figure 16: Changes in coal and solar capacity and share of power generation in India in the STEPS, 2000-2040 (IEA, 2021)

Chapter 4 - Context and Background

In practice:

National Electricity Plan (Central Electricity Authority, 2023)

$\rightarrow$ 25.6 GW of capacity additions between 2022-2027

$\rightarrow$ 25.5 GW of capacity additions between 2027-2032

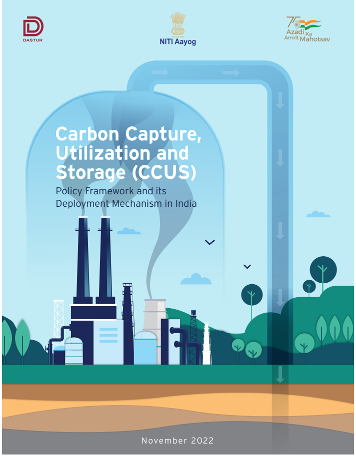
Global Coal Plant Tracker Database (2023)

$\rightarrow$ 32 GW in "construction" stage

$\rightarrow$ 20 GW in "pre-permit" or "permitted" stages

Coal power plants will still represent a heavy share of India's energy production in the upcoming decade(s)

Chapter 4 - Context and Background



"The first step is to map identified industry-wise clusters and suitable storage clusters in India"

India investigates the possibility of deploying CCS

Chapter 4 - Contributions

What is the cost of deploying CCS for Indian coal-fired power plants and what would the network look like?

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Literature review

→ **Context:** CCS studies in India overlook transportation aspects and storage exact locations (Garg et al., 2017; Vishal et al., 2021; Zhang et al., 2022)

Chapter 4 - Contributions

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Literature review

→ **Context:** CCS studies in India overlook transportation aspects and storage exact locations (Garg et al., 2017; Vishal et al., 2021; Zhang et al., 2022)

Contributions

→ Produces a first mapping of the CCS pipeline network in India

→ Determines the CCS cost in India for various policy scenarios

Chapter 4 - Methodology

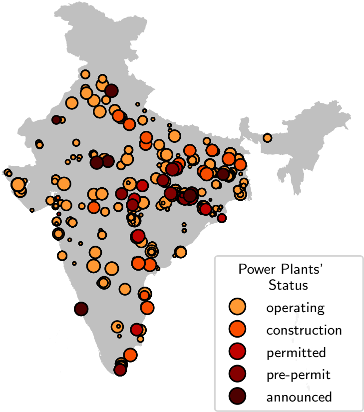

Figure 17: Indian coal power plants (Global Energy Monitor, 2023)

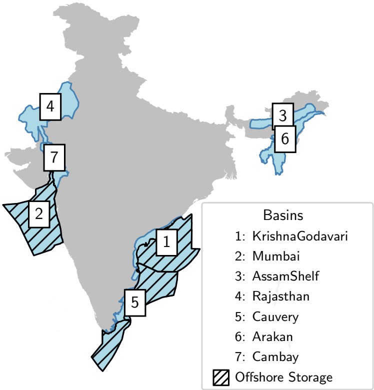

Figure 18: Storage basins (Vishal et al., 2021)

Chapter 4 - Methodology

Mixed Integer Linear Program

$$\begin{aligned} & \min \textit{Total discounted CCS cost} \\ & s.t. \quad \textit{Capture Constraints} \\ & \qquad \textit{Transportation Constraints} \\ & \qquad \textit{Storage Constraints} \end{aligned}$$

Chapter 4 - Methodology

Mixed Integer Linear Program

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→ **Temporal discretization**: 25-year time horizon, five periods of five years

Chapter 4 - Methodology

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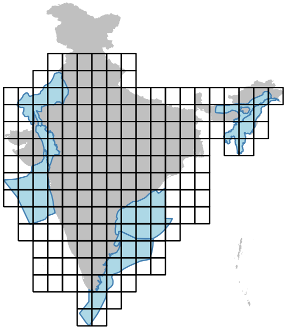

Figure 19: Grid representation

Chapter 4 - Methodology

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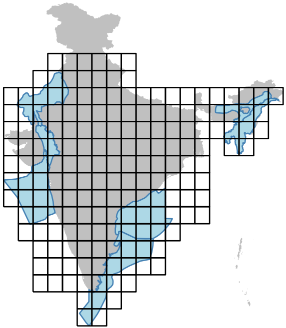
- → **Geographical discretization**: grid representation
- → **Constraints** include physical and investment constraints



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Chapter 4 - Methodology

Mixed Integer Linear Program

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→ **Temporal discretization**: 25-year time horizon, five periods of five years

→ **Geographical discretization**: grid representation

→ **Constraints** include physical and investment constraints

→ Includes **learning effects** of carbon capture

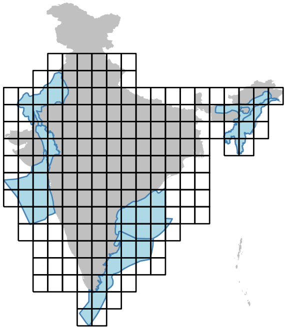

Figure 19: Grid representation

Chapter 4 - Methodology

Four scenarios:

→ **Reference scenario**: processing 50% of emissions through CCS during the time horizon

Chapter 4 - Methodology

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- → **Reference scenario**: processing 50% of emissions through CCS during the time horizon
- → **Offshore scenario**: only offshore storage

Chapter 4 - Methodology

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→ **NewBuild scenario**: new power plants must be equipped with carbon capture

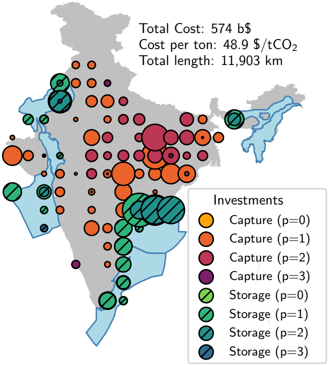
Chapter 4 - Methodology

Four scenarios:

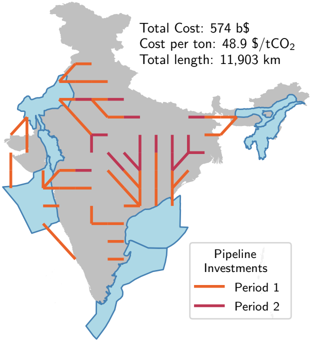
- → **Reference scenario**: processing 50% of emissions through CCS during the time horizon
- → **Offshore scenario**: only offshore storage
- → **NewBuild scenario**: new power plants must be equipped with carbon capture
- → **Capture+ scenario**: increased capture target

Chapter 4 - Results

1. CCS investments follow a *"wait-and-see"* approach



(a) Installed capacities at capture and storage sites.

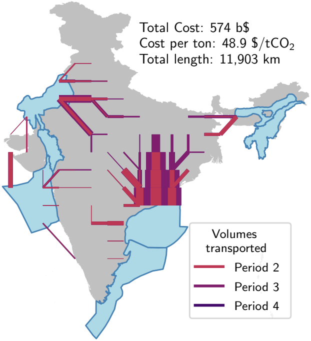


(b) Pipeline network layout.

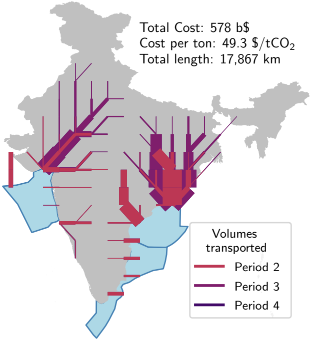
Figure 20: Spatial and temporal evolution of the CCS infrastructure – Reference scenario.

Chapter 4 - Results

2. Network: an eastern backbone and small clusters



(a) Transported volumes – Reference scenario

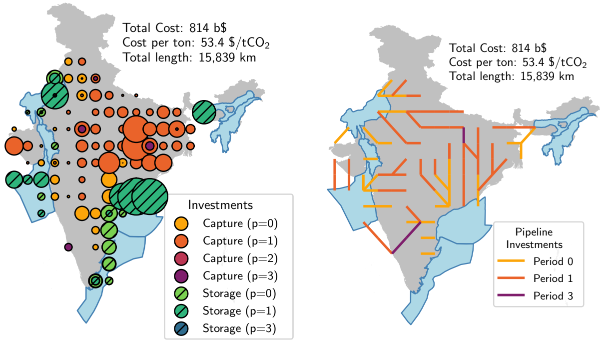


(b) Transported volumes – Offshore scenario

Figure 21: Pipeline utilization in two scenarios

Chapter 4 - Results

3. NewBuild scenario: meager cost increase and less wait-and-see



(a) Installed capacities at capture and storage sites. (b) Pipeline network layout.

Figure 22: Spatial and temporal evolution of the CCS infrastructure – NewBuild scenario.

Chapter 4 - Conclusion

What is the cost of deploying CCS for Indian coal-fired power plants and what would the network look like?

Chapter 4 - Conclusion

What is the cost of deploying CCS for Indian coal-fired power plants and what would the network look like?

Conclusions

→ The Indian CCS network is composed of an eastern backbone transporting emissions to the Krishna-Godavari basin

→ There are also small clusters that can be locally deployed

Policy insights

→ Average CCS cost is around 50$/t$CO_2$

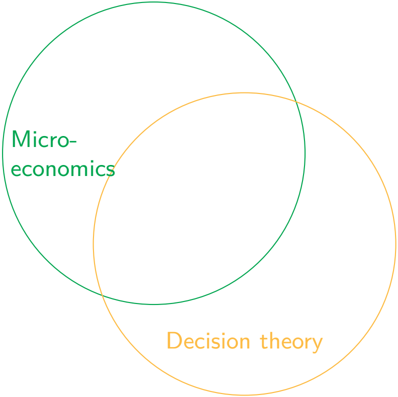
→ International funding could support CCS investment in India

General Conclusion

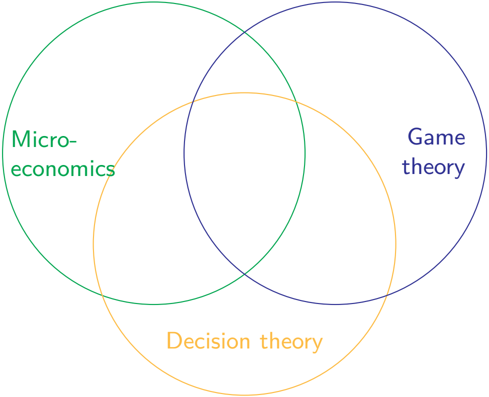
General Conclusion

General Conclusion - Methods

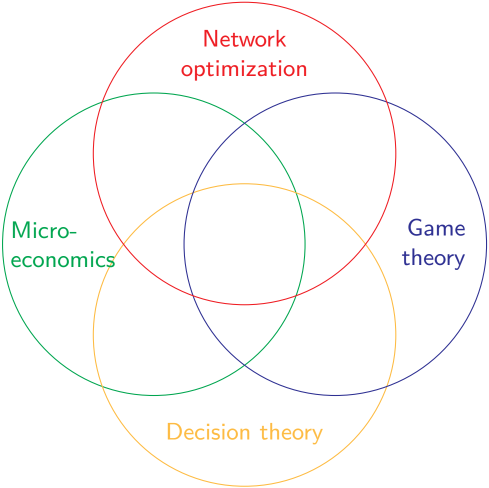
General Conclusion - Methods



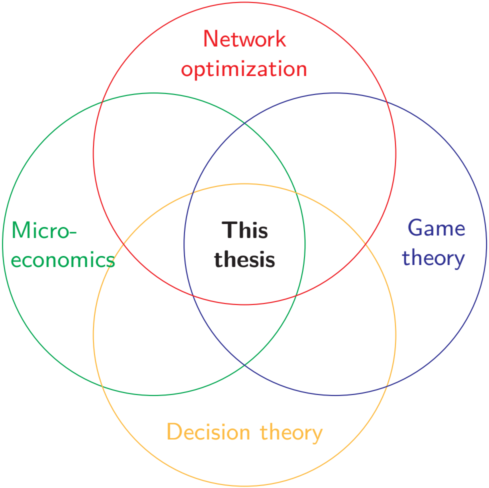
General Conclusion - Methods



General Conclusion - Methods



General Conclusion - Methods



General Conclusion - Policy relevance

Urgent need to scale up CCS... but which priorities?

General Conclusion - Policy relevance

Urgent need to scale up CCS... but which priorities?

Figure 23: Open letter from industry and NGOs from Oct. 23rd 2024

General Conclusion - Policy relevance

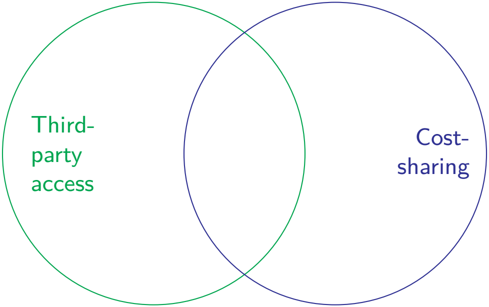
Urgent need to scale up CCS... but which priorities?

Figure 23: Open letter from industry and NGOs from Oct. 23rd 2024

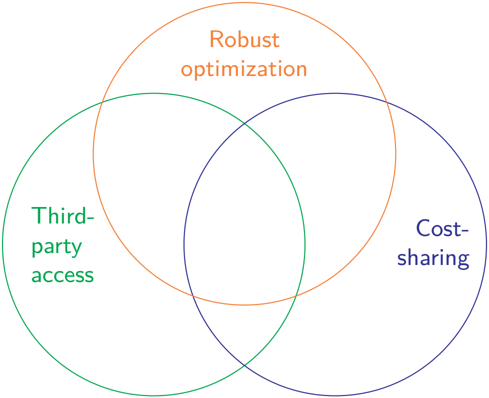
1. Regulation of CCS transport
2. Market for low-carbon products
3. Sufficient access to CCS transport and storage
4. EU CCS Alliance
5. Financial support

General Conclusion - Future research

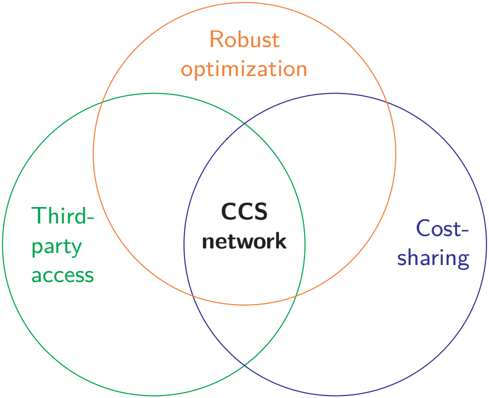
General Conclusion - Future research



General Conclusion - Future research



General Conclusion - Future research



Thank you for your attention

Does transportation matter?

Insights from Massol et al. (2015)

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$\rightarrow$ Average cost of the entire CCS Chain : **59.9 €/tCO_2**

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Insights from Massol et al. (2015)

→ Average cost of the entire CCS Chain : **59.9 €/tCO_2**

Transportation tariffs	Break-even value
a price per tCO_2	
a price per capacity	
a fixed term & a price per tCO_2	
a fixed term & a price per capacity	

Table 7: Break-even carbon price for various non-discriminatory transportation tariffs.

Does transportation matter?

Insights from Massol et al. (2015)

→ Average cost of the entire CCS Chain : **59.9 €/tCO_2**

Transportation tariffs	Break-even value
a price per tCO_2	
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a fixed term & a price per tCO_2	
a fixed term & a price per capacity	**78.0 €/tCO_2**

Table 7: Break-even carbon price for various non-discriminatory transportation tariffs.

Does transportation matter?

Insights from Massol et al. (2015)

→ Average cost of the entire CCS Chain : **59.9 €/tCO_2**

Transportation tariffs	Break-even value
a price per tCO_2	∅
a price per capacity	∅
a fixed term & a price per tCO_2	∅
a fixed term & a price per capacity	**78.0 €/tCO_2**

Table 7: Break-even carbon price for various non-discriminatory transportation tariffs.

Does transportation matter?

Insights from Massol et al. (2015)

$\rightarrow$ Average cost of the entire CCS Chain : **59.9 €/tCO_2**

Transportation tariffs	Break-even value
a price per tCO_2	$\emptyset$
a price per capacity	$\emptyset$
a fixed term & a price per tCO_2	$\emptyset$
a fixed term & a price per capacity	**78.0 €/tCO_2**

Table 7: Break-even carbon price for various non-discriminatory transportation tariffs.

Transportation tariffs can impede the feasibility of CCS projects.

Repurposing existing pipelines

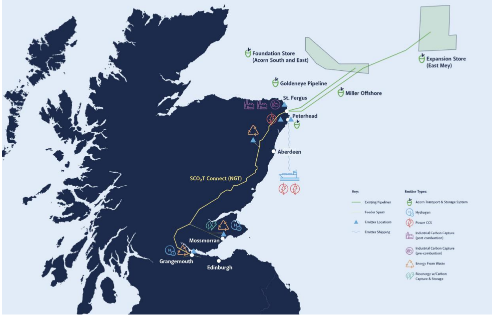

Figure 24: Acorn CCS project in Scotland

- → Repurposing natural gas and oil pipelines
- → Feeder 10: CO_2 as a gas
- → Tradeoff of repurposing limited at 10 $MtCO_2/y$

Algorithm Shapley value

Algorithm 1: First step of the methodology

Data: Emitters N, graph P, pipelines costs y.
$Sh \leftarrow (0, \ldots, 0)$
for $j \in N$ **do**
  for $i \in N$ **do**
    if $i \in \hat{P}^{-1}(j) \cup \{j\}$ **then**
      $Sh_i \leftarrow Sh_i + \frac{y_{jP(j)}}{|\hat{P}^{-1}(j) \cup \{j\}|}$
    else
      $Sh_i \leftarrow \varphi_i$
    end
  end
end
Result: Sh

Back

Mixed Integer Linear Program

$$
\begin{aligned}
\min_{\delta_p, q_p^+, q_p^-} \quad & \sum_{p \in P} \left[C^{inv,fix} \delta_p + C^{inv,var} \left(q_p^+ + q_p^- \right) + C^{om} \left(q_p^+ + q_p^- \right) \right] L \\
\text{s.t.} \quad & \sum_{p \in P} I_{p,i} \left(q_p^+ - q_p^- \right) + Q_i = 0, && \forall i \in N \\
& \sum_{p \in P} I_{p,k} \left(q_p^+ - q_p^- \right) \geq 0, && \forall k \in K \\
& q_p^+ + q_p^- \leq \delta_p M, && \forall p \in P \\
& \delta_p \in \{0, 1\},\ q_p^+ \geq 0,\ q_p^- \geq 0, && \forall p \in P
\end{aligned}
$$

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Capture cost

Industrial sector	Carbon avoided cost [€/$tCO_{2,\text{avoided}}$]	Capture rate [-]
Ammonia	20	0.8
Cement	50	0.9
Steel	60	0.9
Pulp & paper	60	0.9
Refineries and petrochemicals	100	0.7

Table 8: Carbon capture assumptions by sector

The jury is deliberating