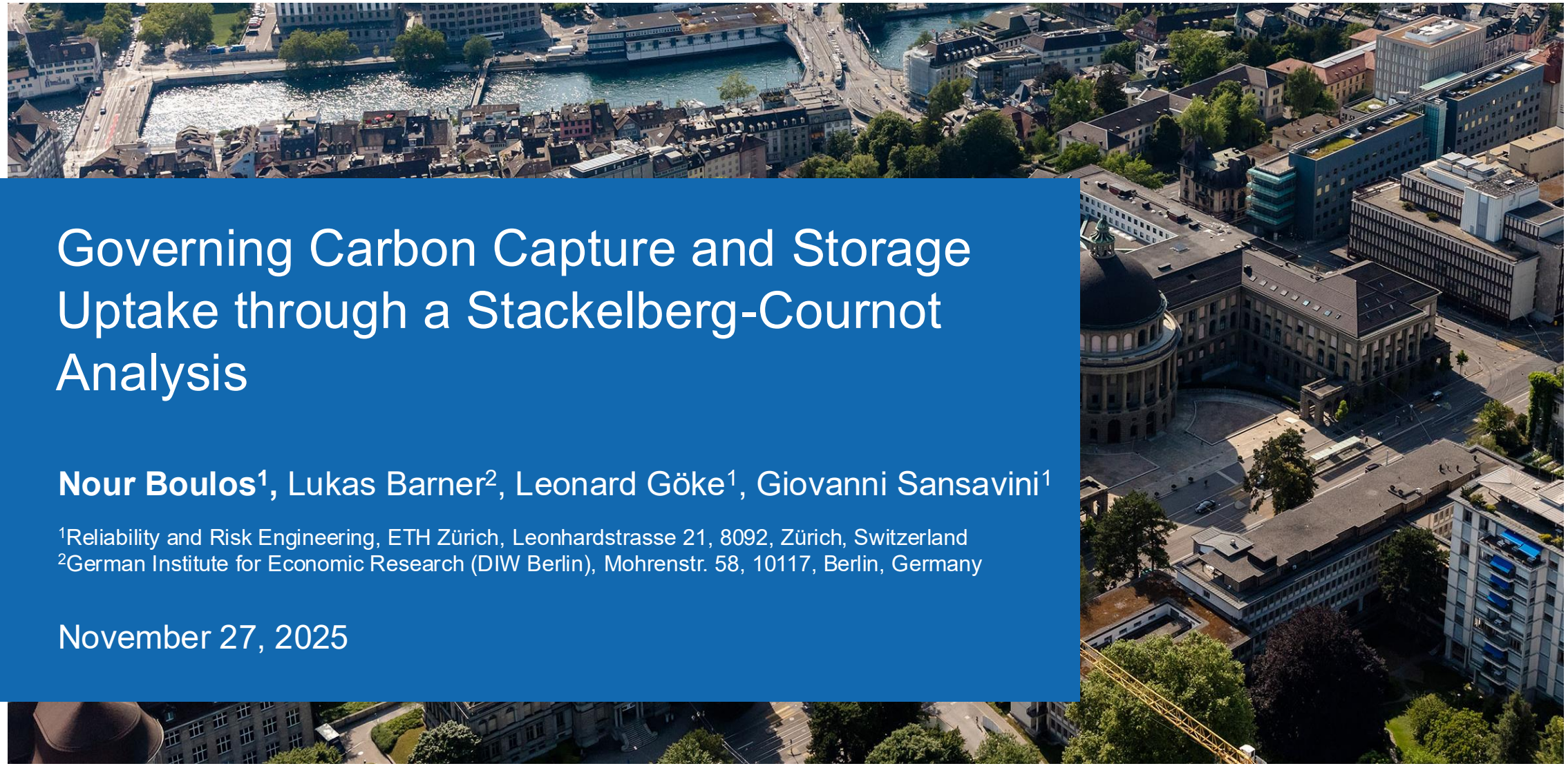

Governing Carbon Capture and Storage Uptake through a Stackelberg-Cournot Analysis

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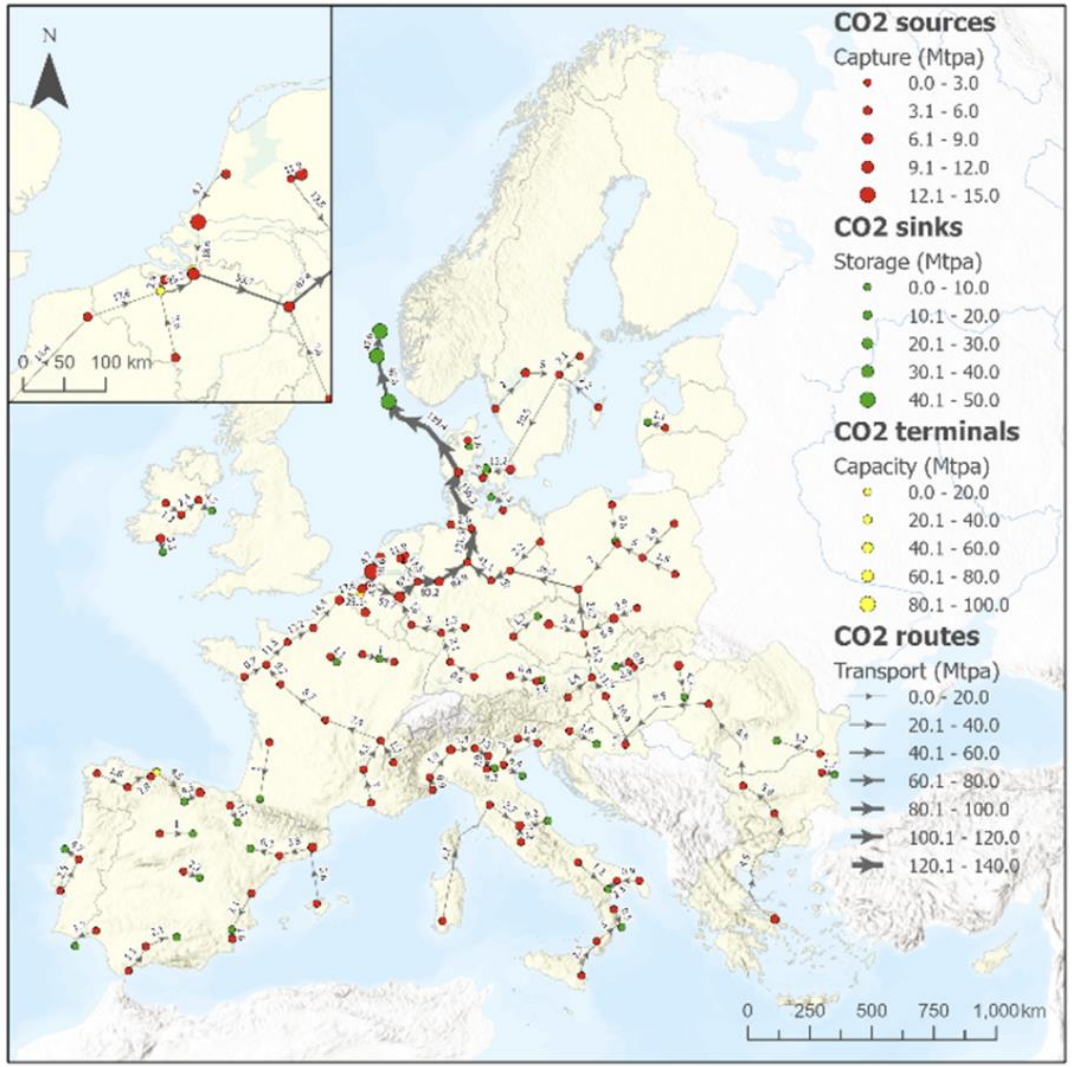
Introduction

- NZIA target: injection of 50MtCO_2/year by 2030 [1]
- Published network rollout in (regions of) Europe [2, 3]
- Network operation in Europe and Switzerland in 2025 [2, 3]

Why is CCS not implemented yet?



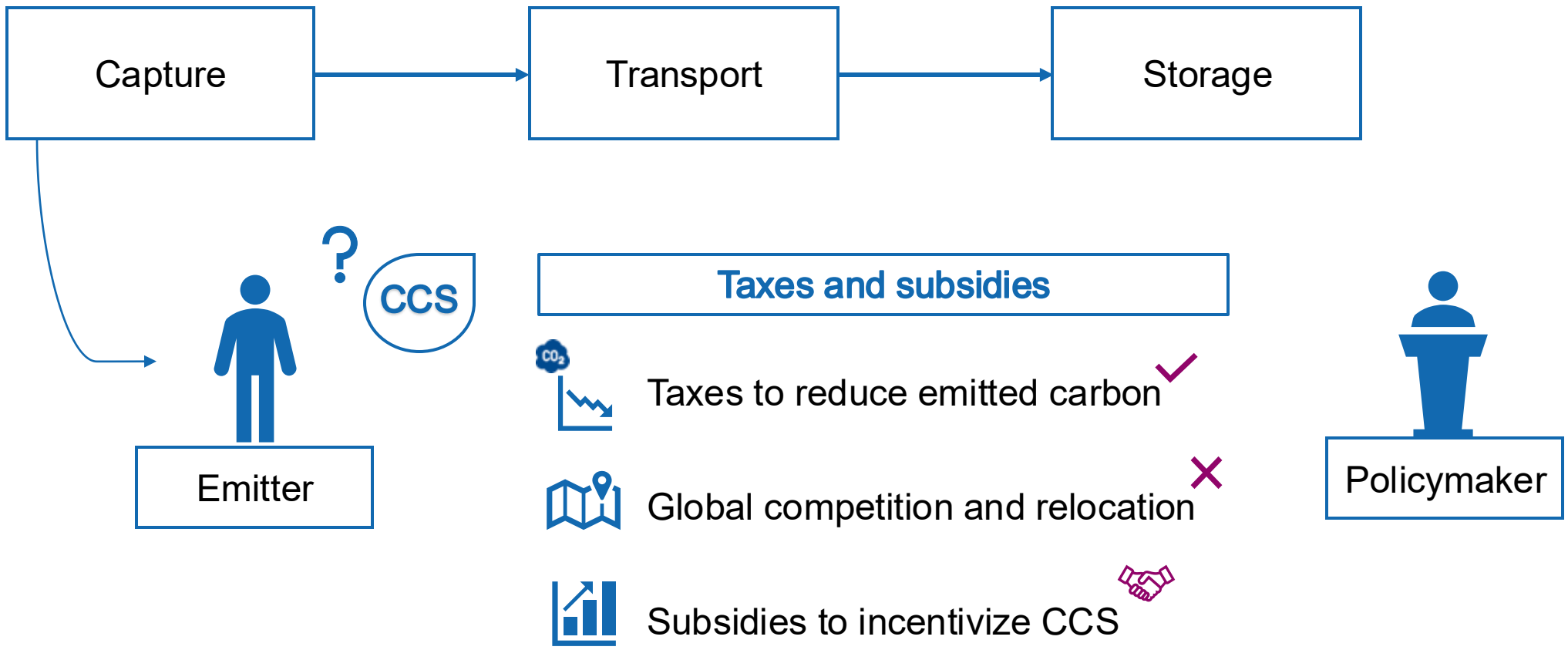
CO2 network in 2050 (EU + NO+UK)
© EU 2024

[1] Joint Research Centre. (2024, February 6). *CO2 transport infrastructure: Key to achieving climate neutrality by 2050*. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/co2-transport-infrastructure-key-achieving-climate-neutrality-2050-2024-02-06_en
[2] Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., & Mazzotti, M. (2022). Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. *International Journal of Greenhouse Gas Control*, *117*, 103635. https://doi.org/10.1016/j.ijggc.2022.103635
[3] Gabrielli, P., Campos, J., Becattini, V., Mazzotti, M., & Sansavini, G. (2022). Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: The cost of resilience. *International Journal of Greenhouse Gas Control*, *121*, 103797. https://doi.org/10.1016/j.ijggc.2022.103797

Introduction

Why is CCS not implemented yet?

CCS value chain



Introduction

Policymaker

Taxes and subsidies

FINANCIAL TIMES

Climate change ■ Add to myFT

Norway launches full-scale industrial carbon capture project with billions in subsidies

CO_2 shipped to North Sea to be injected into reservoirs of oil majors

CAPTURE POLICY STORAGE

Japan To Offer Subsidies For Carbon Capture And Storage

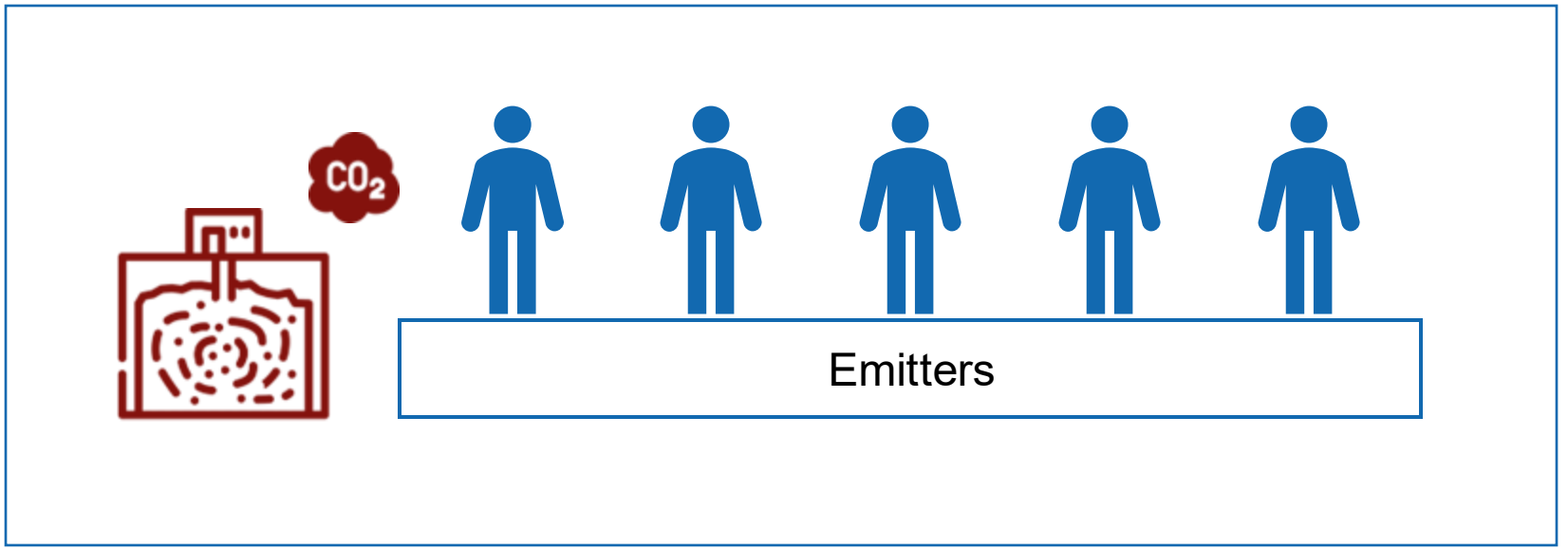
by **Violet George** · January 15, 2025 · 1 minute read

Policy

EU approves Germany's €5bn subsidy scheme for industries to switch to hydrogen, carbon capture and electrification

Introduction

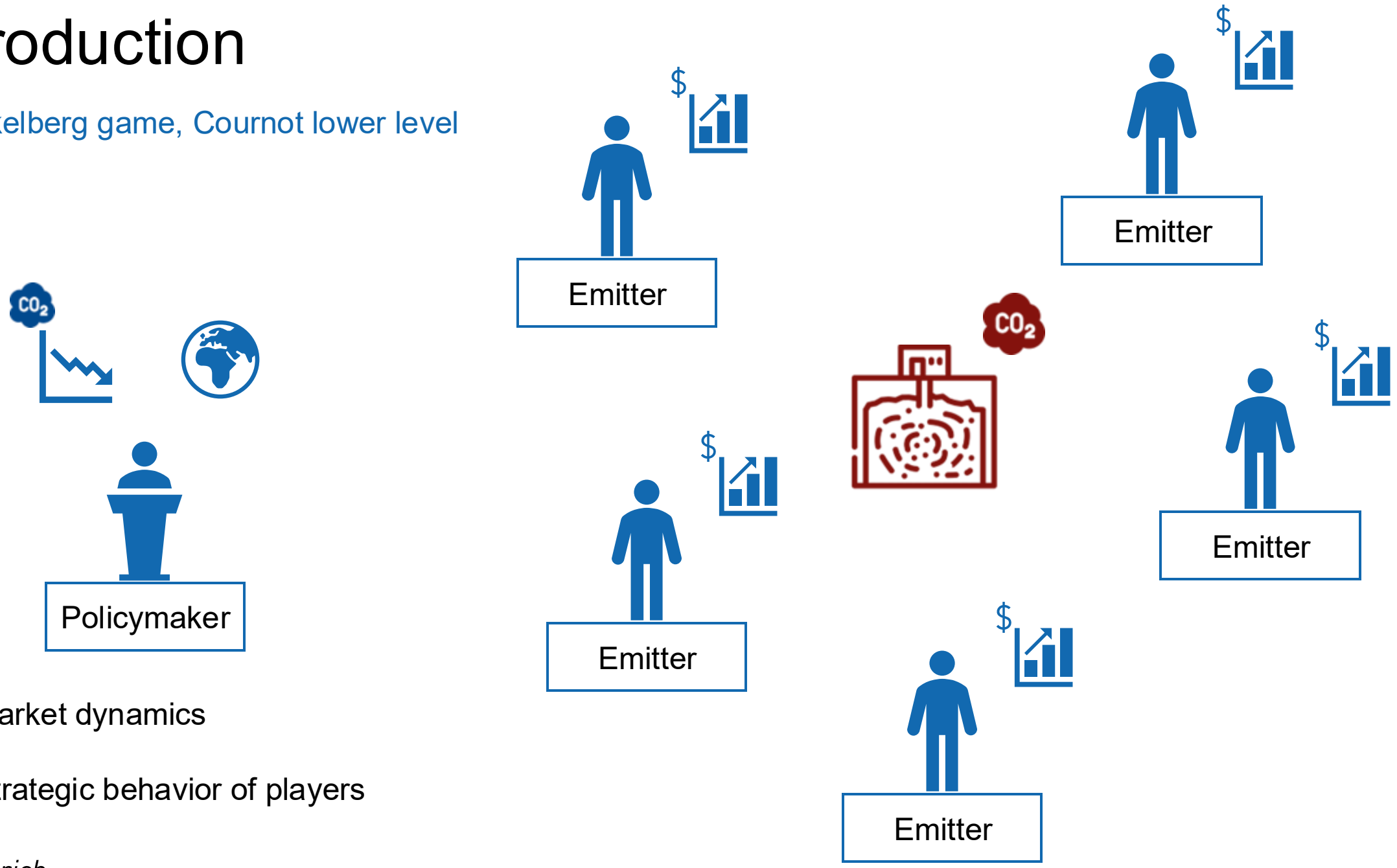
Current models: social planner problem



- ✗ Market dynamics
- ✗ Strategic behavior of players

Introduction

Stackelberg game, Cournot lower level



- ✓ Market dynamics
- ✓ Strategic behavior of players

Introduction

Stackelberg game, Cournot lower level

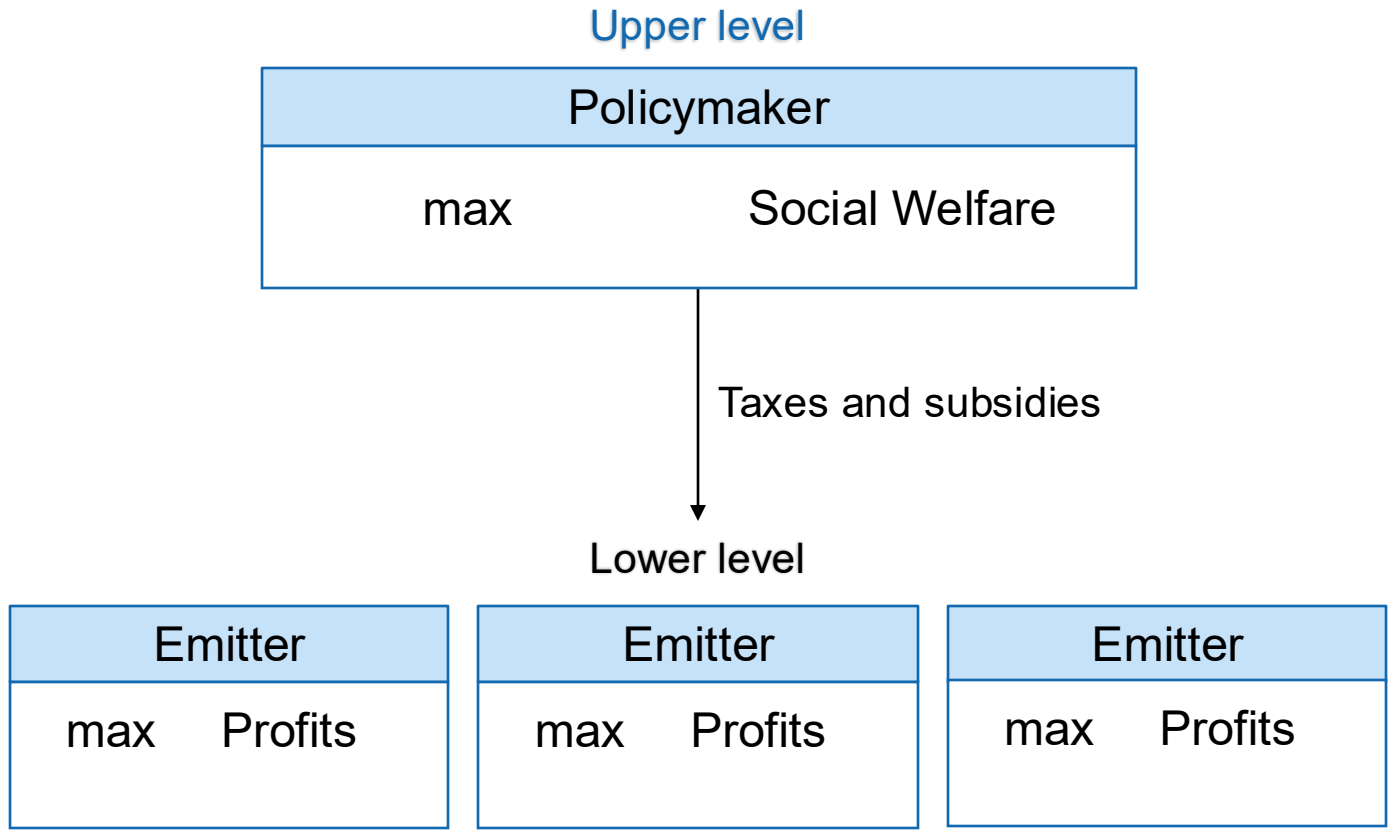
Bi-level optimization problem

Sequential game: one leader, multiple followers

Leader's advantage; moves first

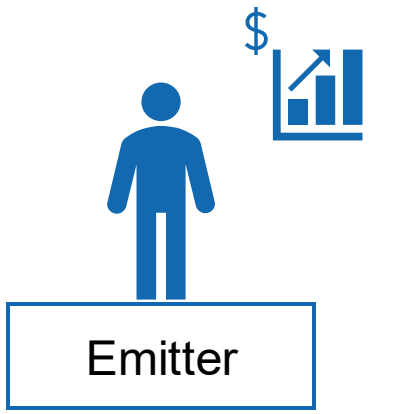
Followers' reaction; respond to leader's policy

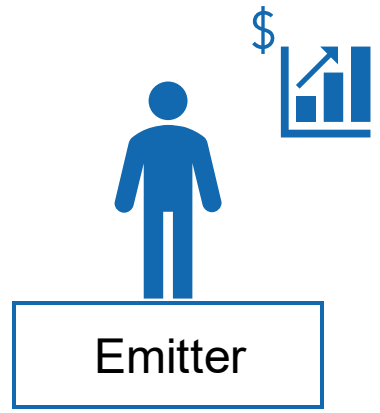
Backward induction: leader anticipates the response of followers

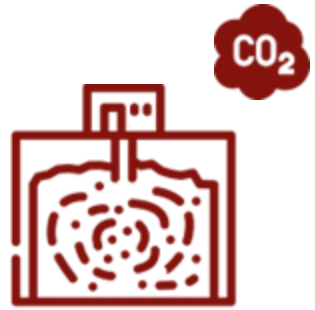


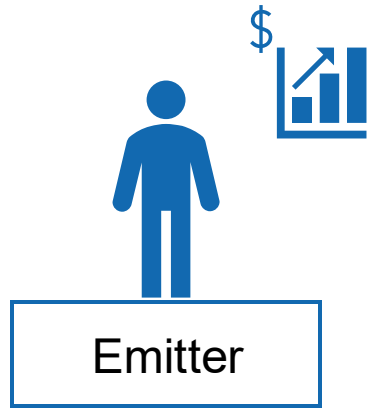
Introduction

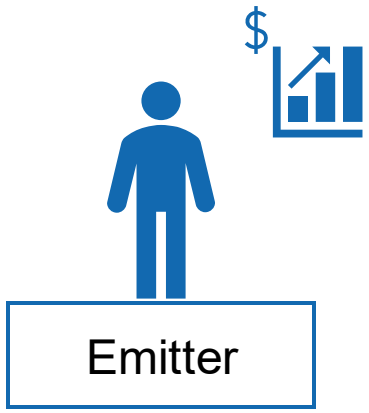
Stackelberg game, Cournot lower level

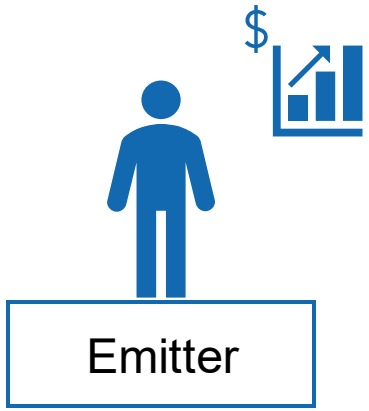










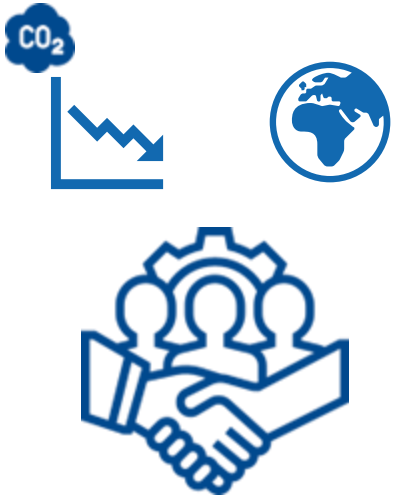


How do taxes and subsidies affect the social welfare?

How do emitters react? What are their profits and how much do they capture?

Method

Social planner, global optimum and benchmark



Social planner		
$\max_{q_i^{cap}, e_i^{CO_2}}$	Social Welfare =	+ Emitters profits from production − Capture costs − Storage costs − Transport costs
s.t.	Technical constraints Emission constraint: $\sum e_i^{CO_2} \leq E^{CO_2} : (\mu^{CO_2})$	

Social planner cost of carbon

Method

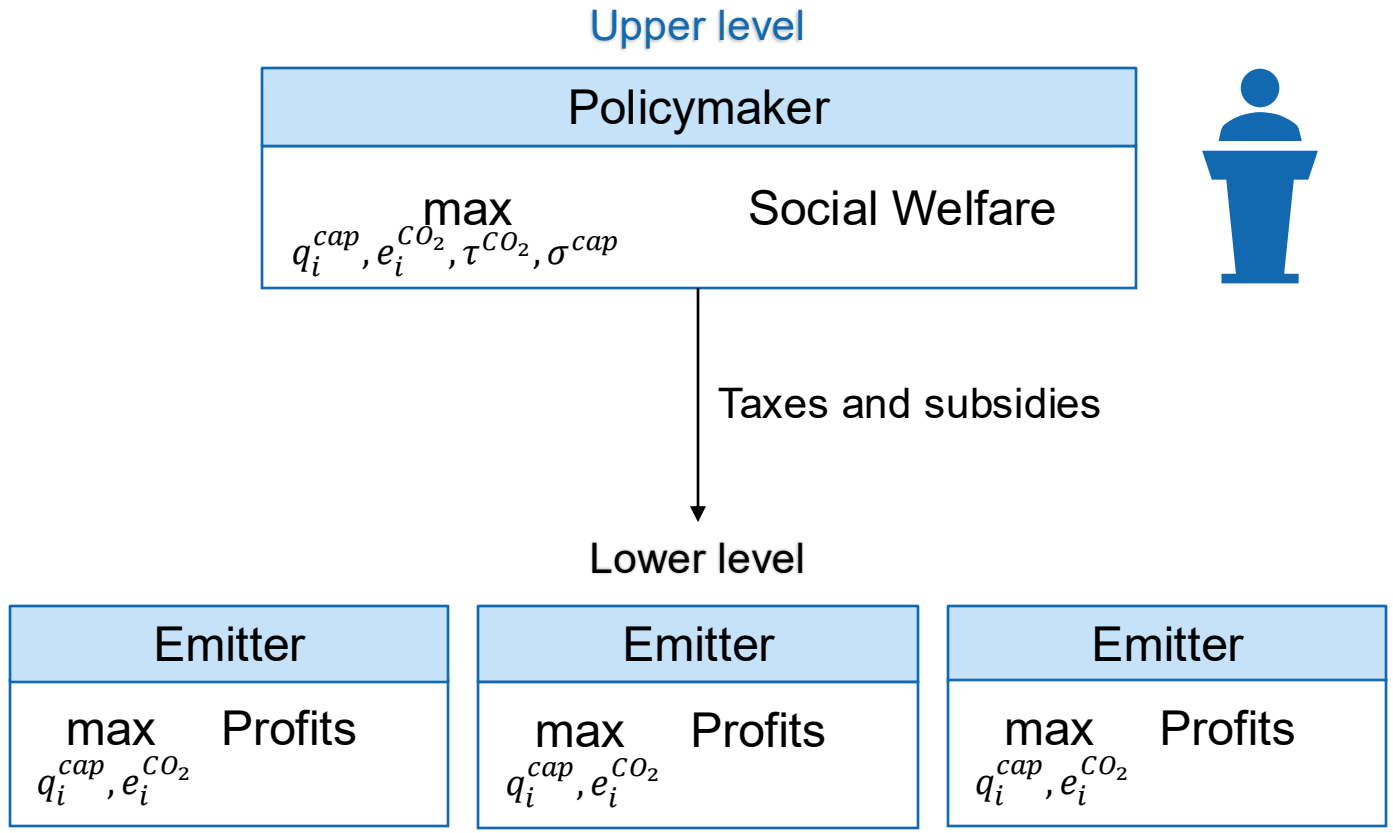
Stackelberg game, Cournot lower level

Emitter's profits:

- ✚ Profits from production
- ▬ Capture costs
- ▬ Storage costs, price paid to storage operators
- ▬ Transport costs
- ✚ Capture subsidy
- ▬ Released CO_2 tax

Social welfare:

- ✚ Emitters' profits
- ✚ Storage revenues
- ▬ Storage costs
- ✚ Released CO_2 tax
- ▬ Capture subsidy
- ▬ Social planner cost of carbon $\sum e_i^{CO_2} \mu^{CO_2}$

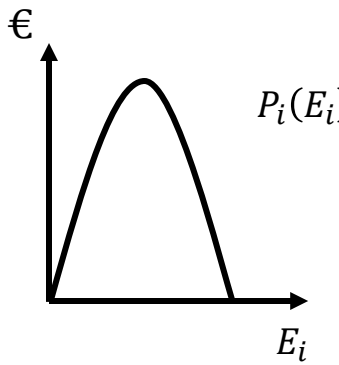


Method

Stackelberg game, Cournot lower level

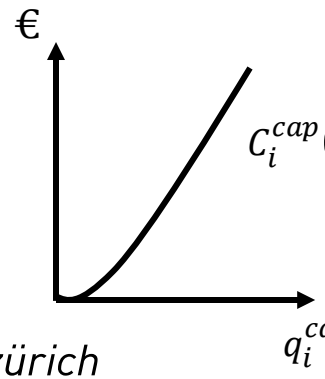
Emitter's profits:

- ✚ Profits from production, concave quadratic function



$$P_i(E_i) = -P_{i,1}E_i^2 + P_{i,2}E_i$$
$$P_{i,1}, P_{i,2} \geq 0$$

- ▬ Capture costs, convex quadratic function



$$C_i^{cap}(q_i^{cap}) = C_{i,1}^{cap} q_i^{cap\,2} + C_{i,2} q_i^{cap}$$
$$C_{i,1}^{cap}, C_{i,2}^{cap} \geq 0$$

Upper level

Policymaker

$$\max_{q_i^{cap}, e_i^{CO_2}, \tau^{CO_2}, \sigma^{cap}} \text{Social Welfare}$$

Taxes and subsidies

Lower level

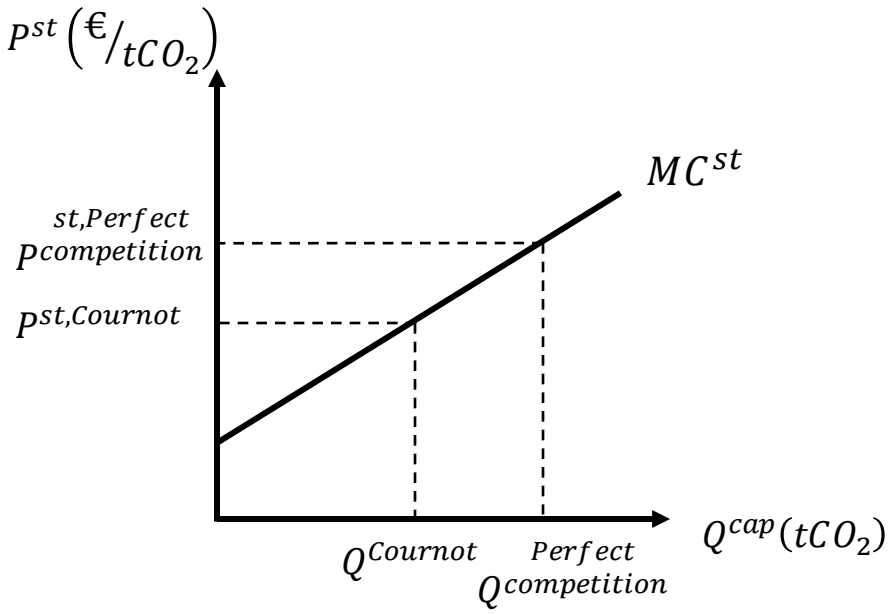
Emitter	Emitter	Emitter
$\max_{q_i^{cap}, e_i^{CO_2}}$ Profits	$\max_{q_i^{cap}, e_i^{CO_2}}$ Profits	$\max_{q_i^{cap}, e_i^{CO_2}}$ Profits

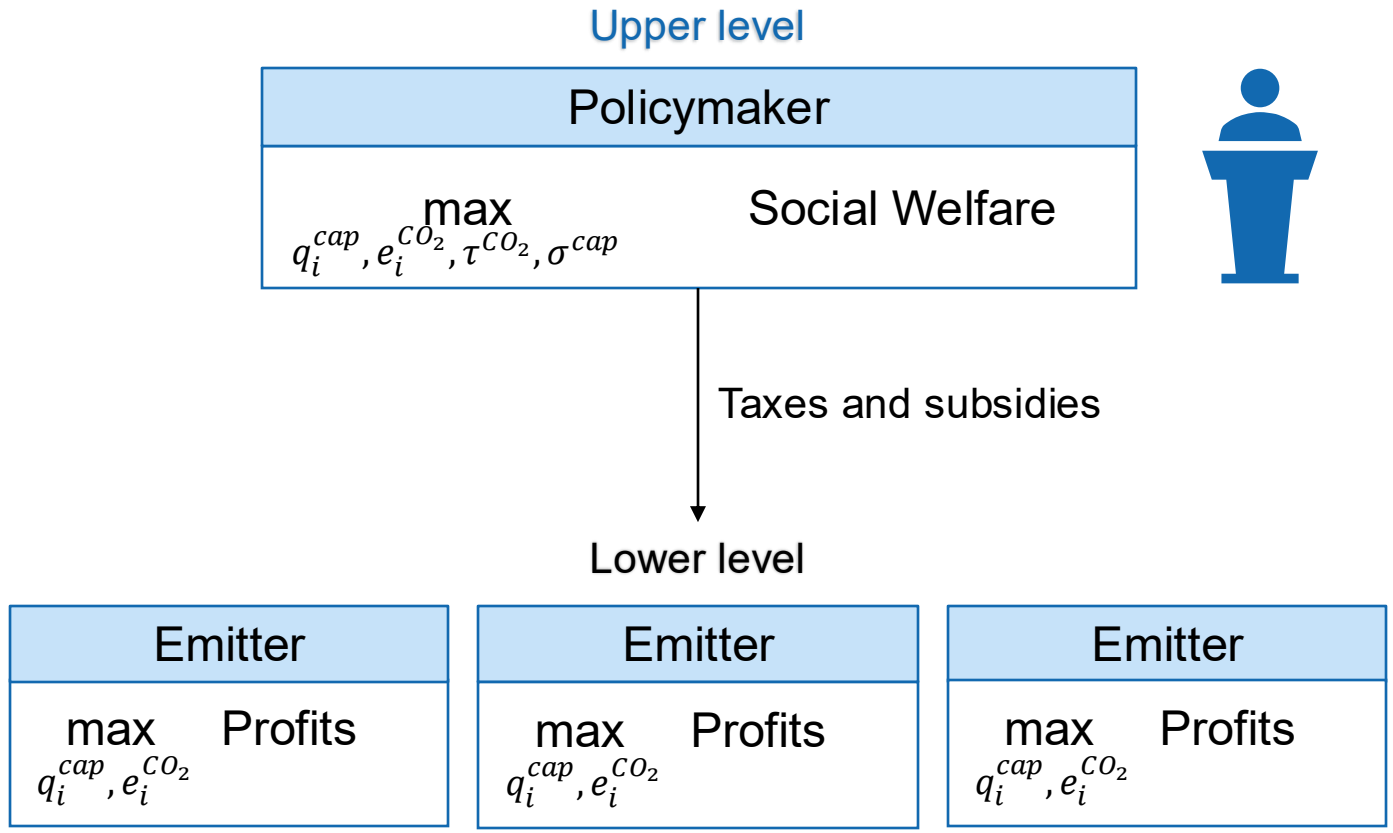
Method

Stackelberg game, Cournot lower level

Emitter's profits:

- Storage costs, price paid to storage operators





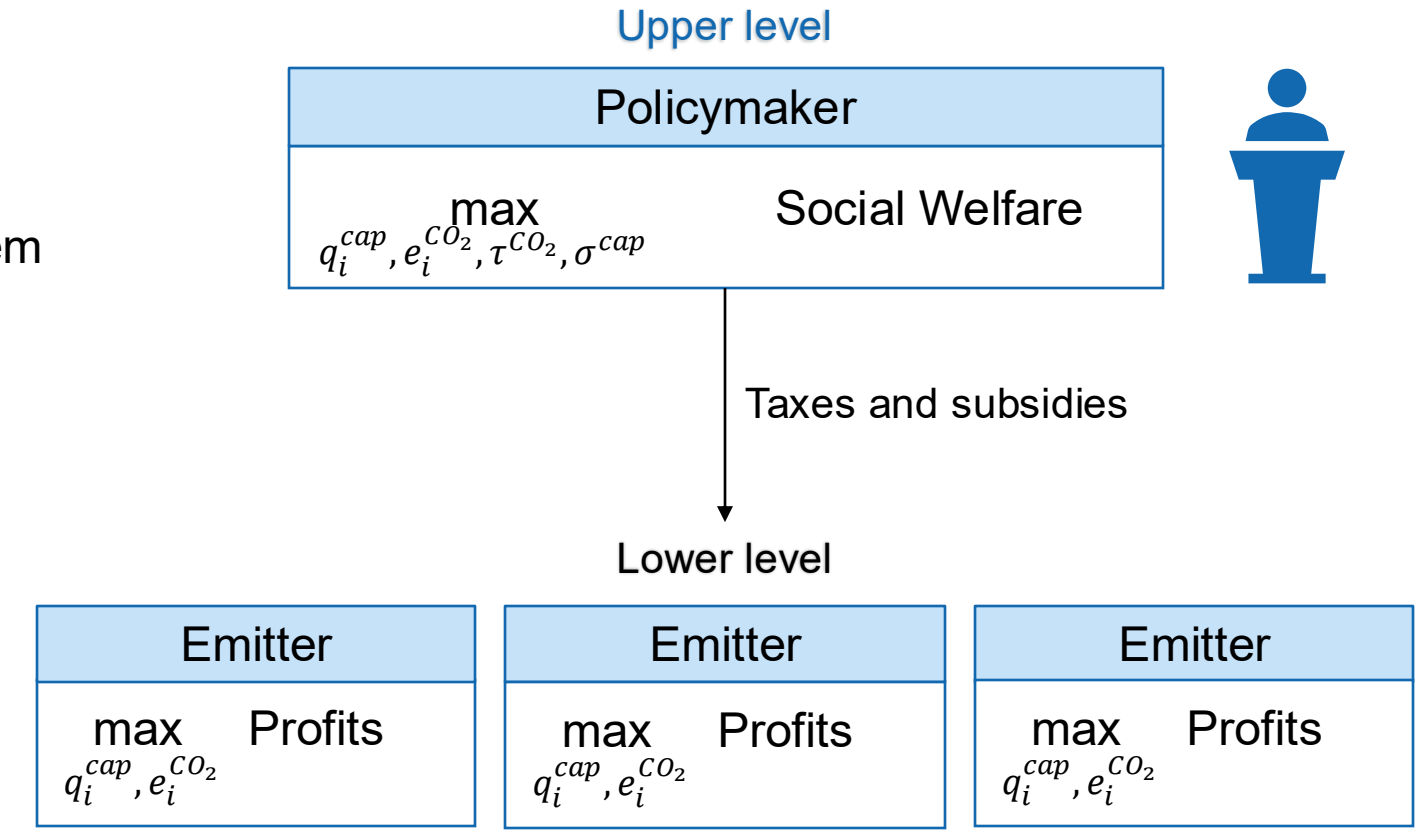
Method

Stackelberg game, Cournot lower level

Solution algorithm:

Lower level convex optimization problem

Reformulate into KKT conditions



Method

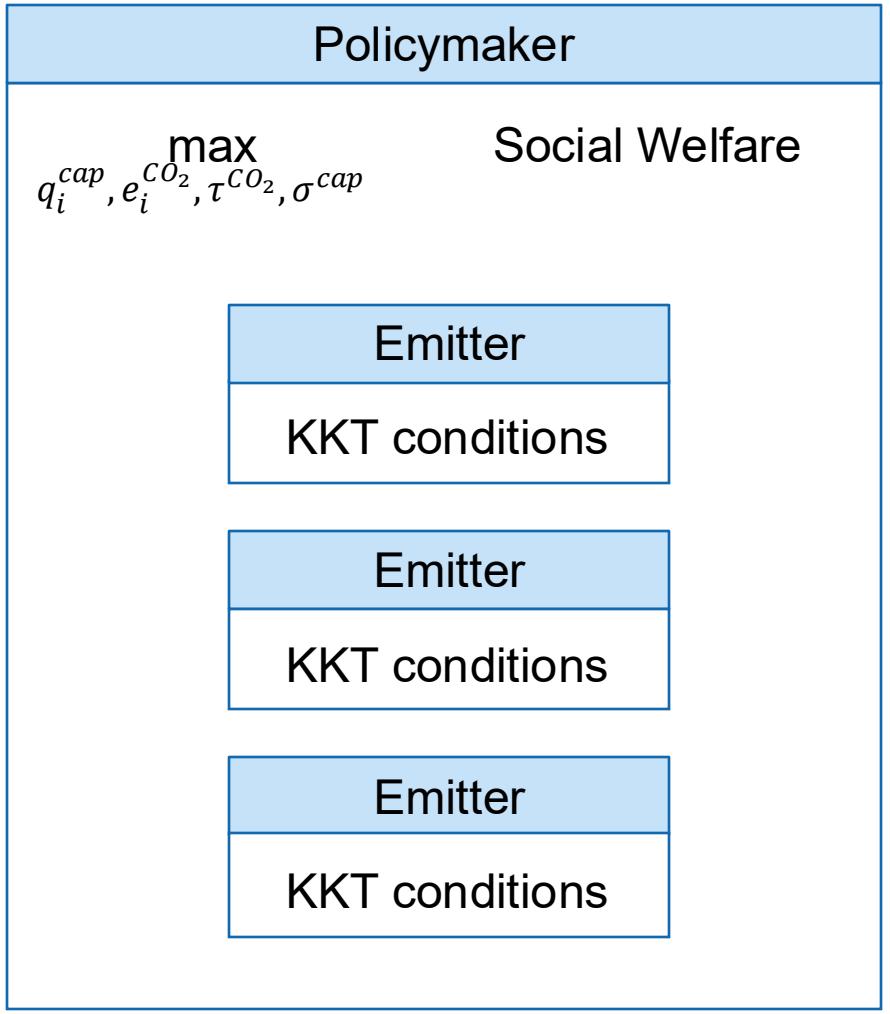
Stackelberg game, Cournot lower level

Solution algorithm:

Lower level convex optimization problem

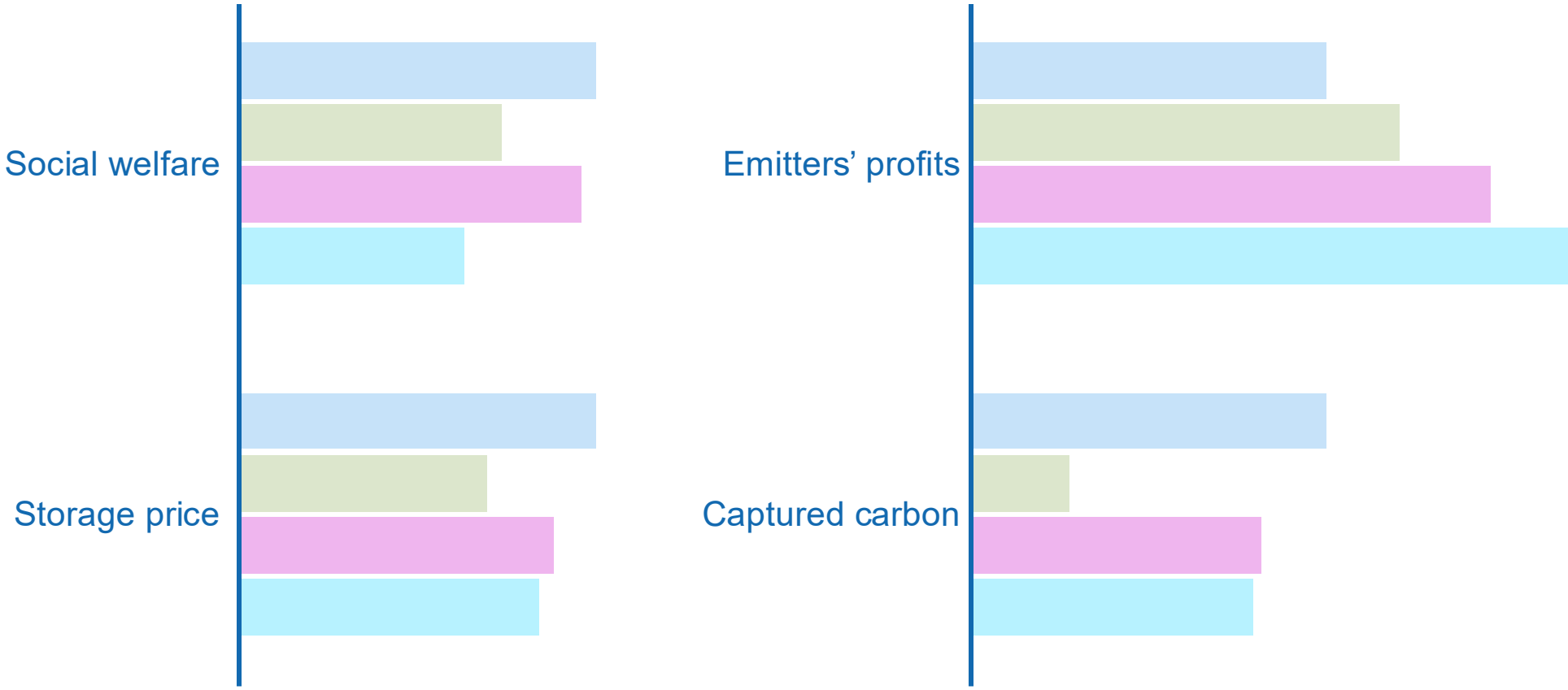
Reformulate into KKT conditions

Single-level optimization problem, complementarity constraints



Results – qualitative

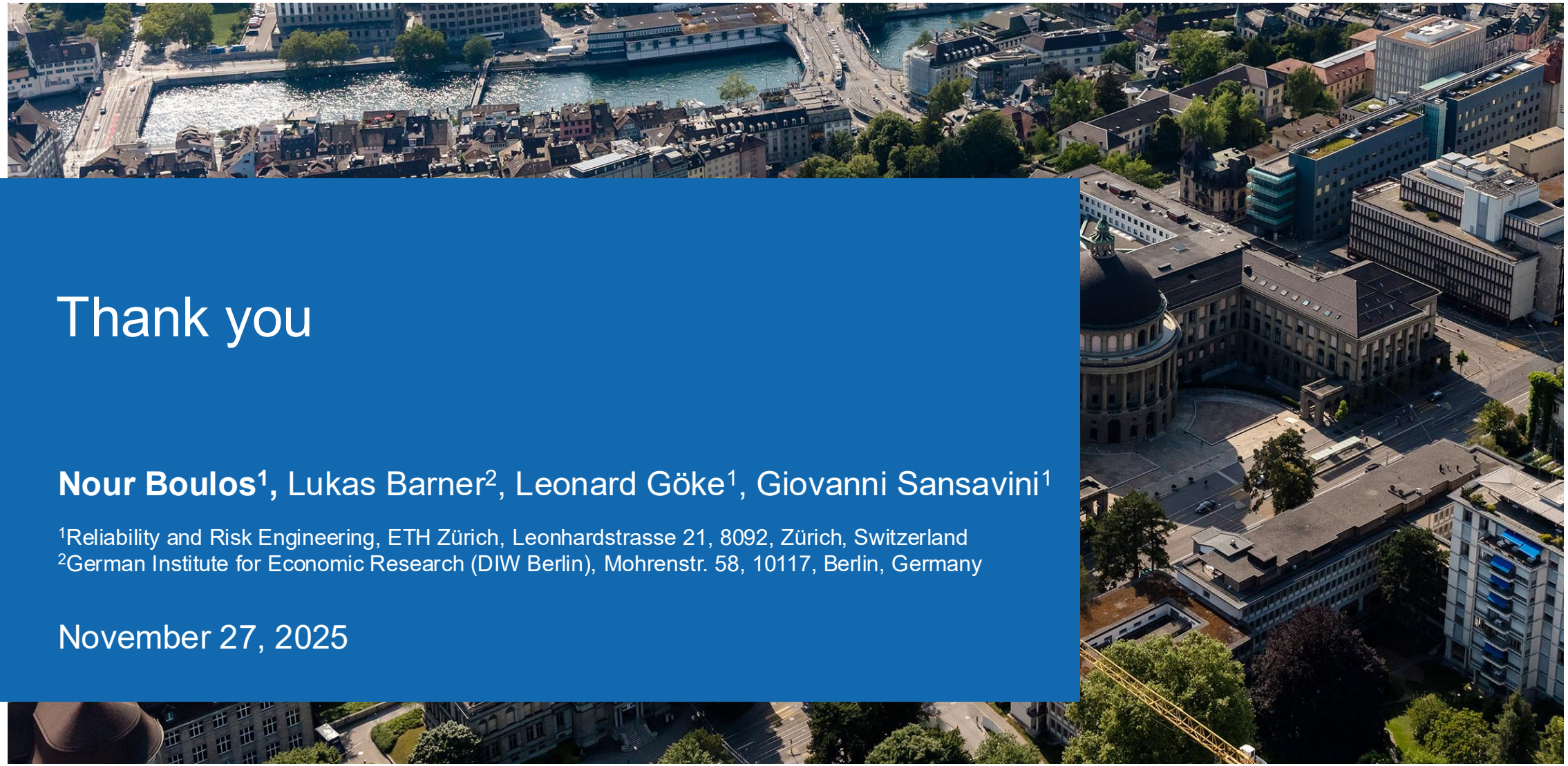
Stackelberg game, Cournot lower level



Next steps

Stackelberg game, Cournot lower level

- Define a case study
- Add spatial resolution
- Parametrize profit and cost functions



Thank you

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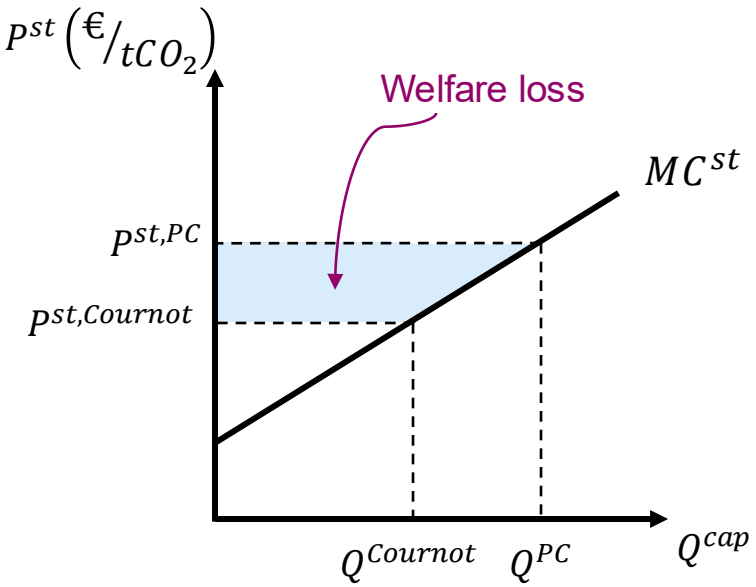
November 27, 2025

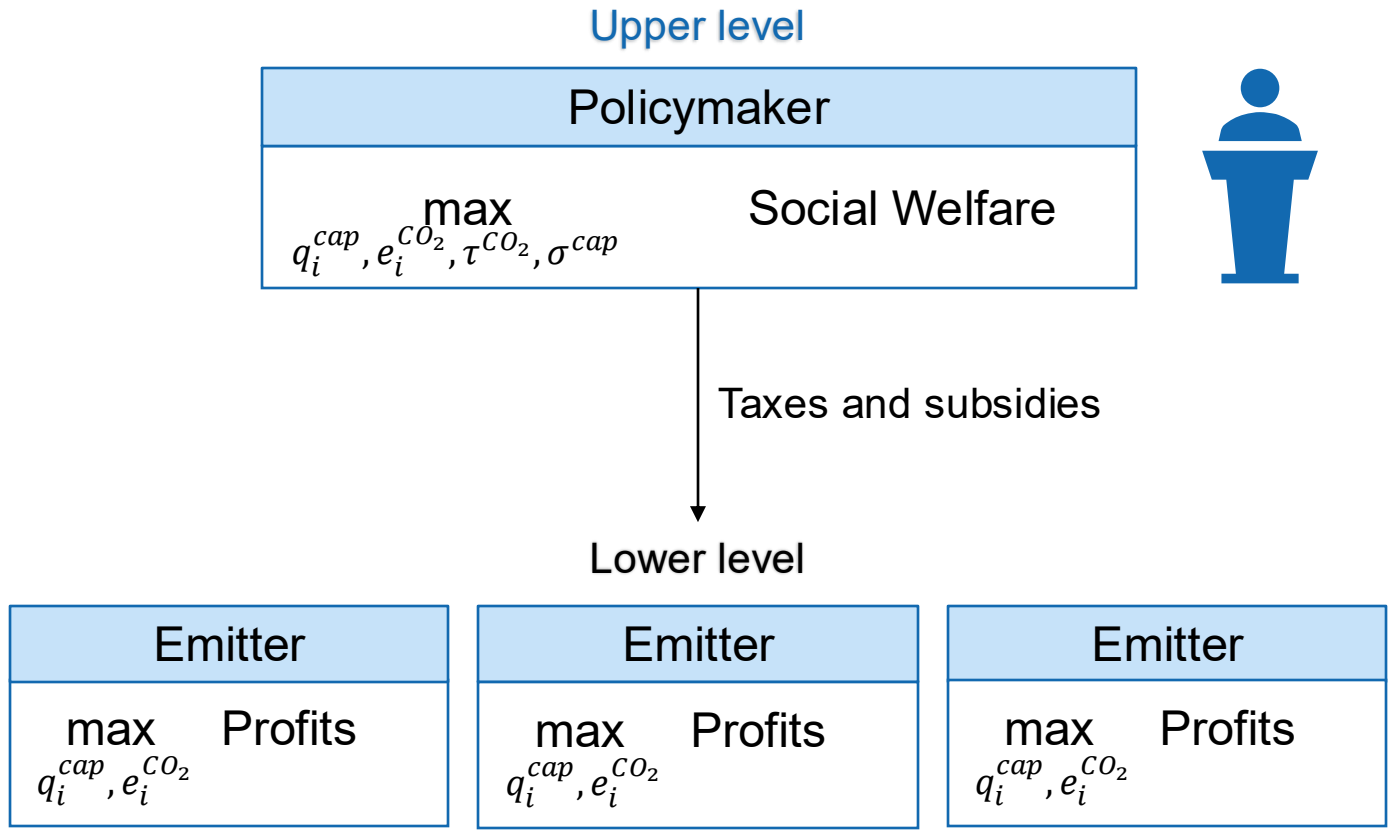
Method

Stackelberg game

Emitter's profits:

- Storage costs, price paid to storage operators





Results

Stackelberg game, equivalent to social planner

Equivalence conditions:

1. $\tau^{CO_2} = \mu^{CO_2}$
2. $\sigma^{cap} = 0$
3. Emitters in perfect competition against storage price

➡ Social planner solution