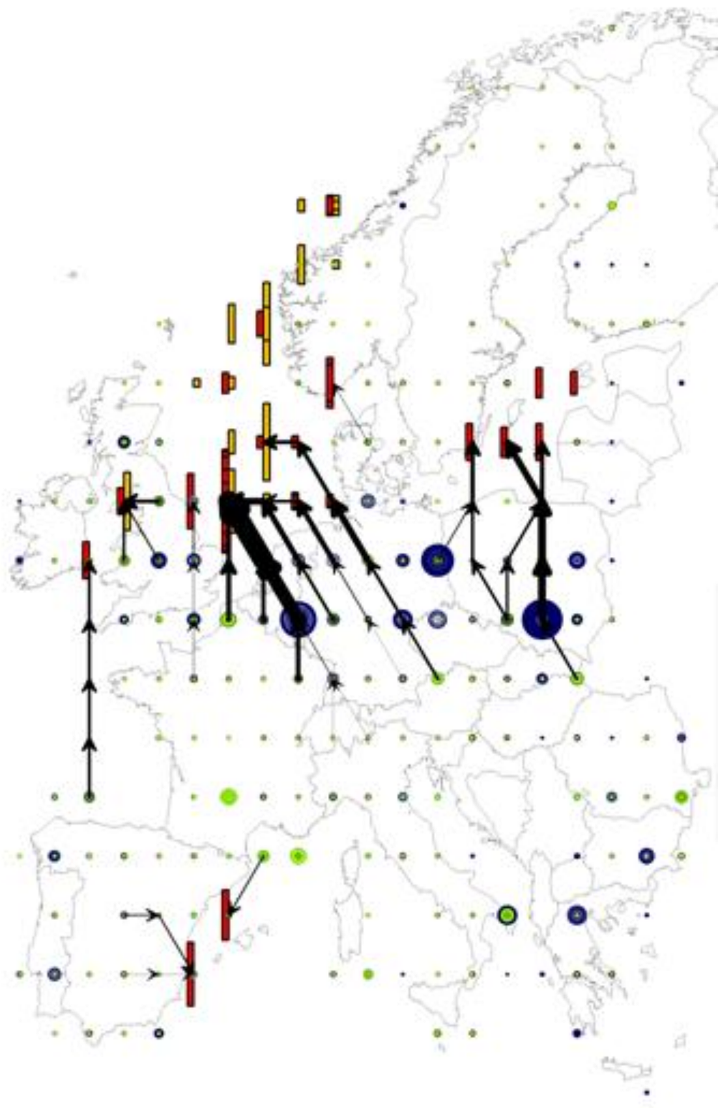


Modeling a European Carbon Capture, Transport and Storage (CCTS) Infrastructure for the Industrial Sector

Workgroup for Economics and Infrastructure Policy (WIP), TU Berlin

Trans-Atlantic INFRADAY Conference
Washington, DC November 11th, 2011

Christian von Hirschhausen
Johannes Herold
Pao-Yu Oei

Agenda

1) Motivation

2) Description of the Model CCTSMOD

3) Implemented Data

4) Scenario Runs

5) Results of the Scenarios

6) Conclusion and Further Research

Motivation

Carbon Capture Transport and Storage – CCTS

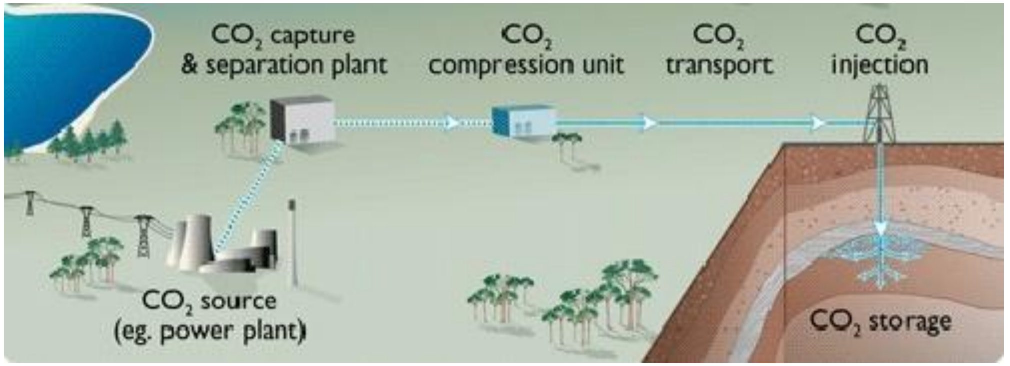
- 70 % higher CO_2 mitigation costs without CCTS (IEA, 2009)
- few running projects (esp. Industry)

European Union

- Switch to almost full decarbonization of the electricty sector by 2050
- Any need for CCTS at all?

Industry Sector

- Unavoidable CO_2 emissions
- Solution for total decarbonization



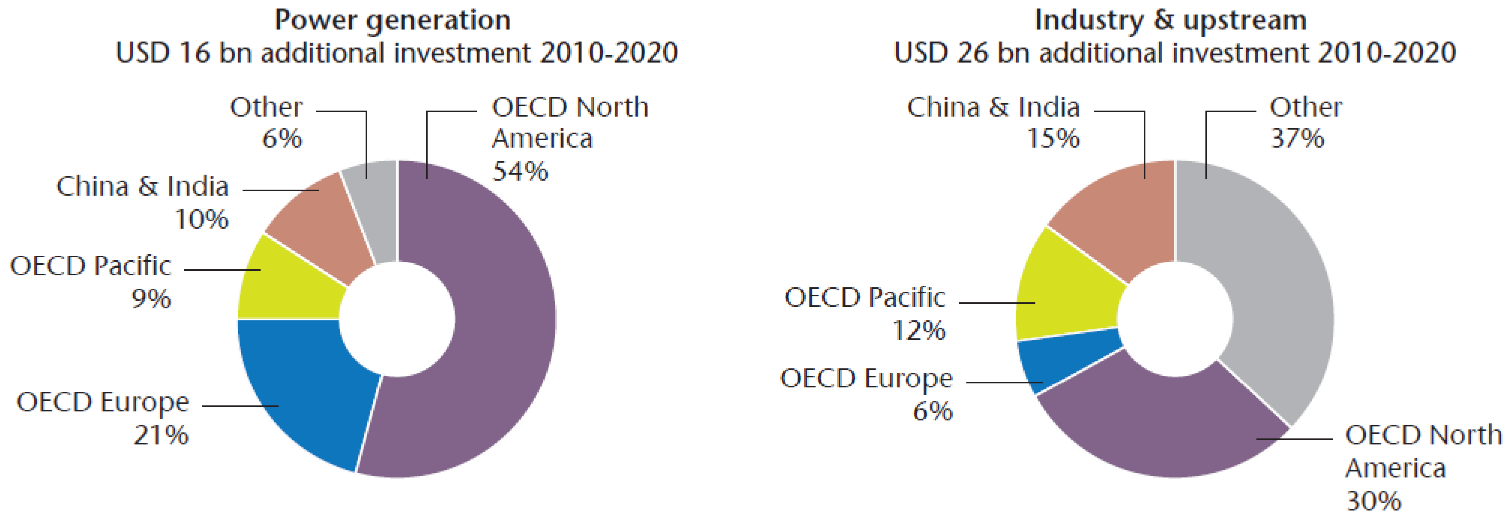
Source: Clean Technica

Climate modeler's hopes

Until 2050 (IEA, 2009)**:**

- 3400 CCTS projects worldwide
- Investments of 3 trn.US$, 50 % in the power generation sector, 14 % in the upstream sector and 36 % in the industrial sector
- 200,000-360,000 km of pipelines, mostly in North America, China, OECD Europe

Global investment into CCTS needed to "kick-start" CCTS deployment



CCTS in Industrial Applications

- **Cement: responsible for more than 5 % of global anthropogenic CO_2 emissions**
  - Production of 1 ton Portland cement results in 0.65 – 0.92 tons of CO_2
  - Alternative production processes under development, but no major break through

- **Iron/Steel: accounts for 19 % of final energy use and a quarter of direct CO_2 emissions from the industry sector**
  - World average: 1 t steel = 2.2 t CO_2, best practice 1.8 t CO_2
  - Direct iron production in combination with CO_2 neutral hydrogen production?

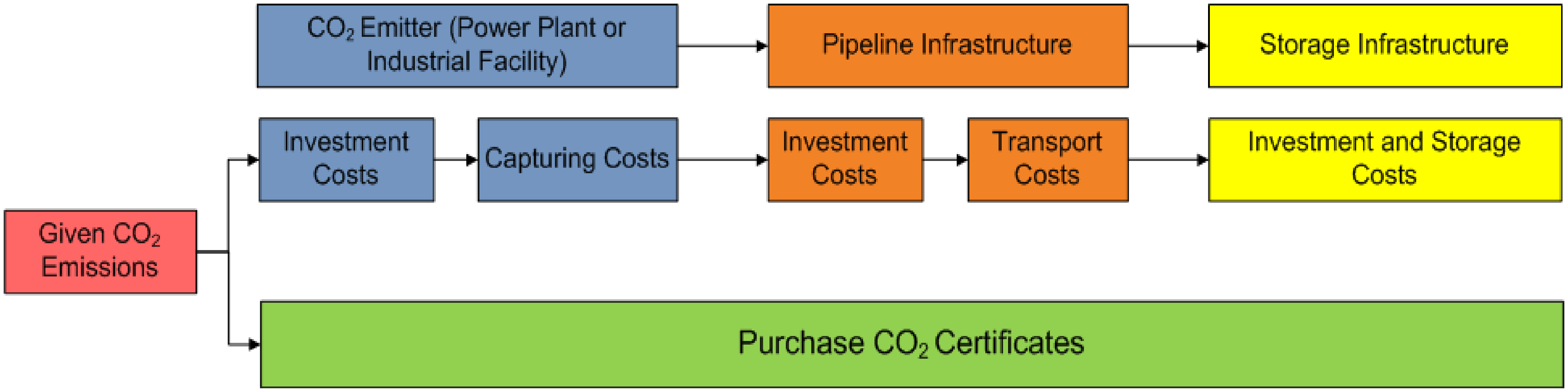
- **Refineries: the use of hydrogen will increase with the use of heavy oils, oil sands and oil shale**
  - Use of “green” hydrogen possible, but uneconomical

→ CCTS in energy-intensive industries the “most” likely midterm CO_2 abatement technology

Source: UNIDO, 2010

Decision Tree of the CCTSMOD

- Omniscient planner designs cost-optimal CCTS infrastructure given costs for infrastructure and CO_2 Certificates
- CO_2 Certificate price as initiator for CCTS development
- Time horizon 2010-2050
- Solved as a **M**ixed **I**nteger **P**roblem (MIP) with the CPLEX Solver in GAMS



Model: Cost Minimization Problem

$$\min_{\substack{inv\_x_{Pa},\, x_{Pa},\, z_{Pa},\, plan_{ija},\\ inv\_f_{ijda},\, f_{ija},\, inv\_y_{Sa}}} h = \sum_a \left[\left(\frac{1}{1+r}\right)^{(year_a - start)} \cdot \left(\sum_P \left[c\_inv\_x_P \cdot inv\_x_{Pa} + c\_ccs_{Pa} \cdot x_{Pa} + cert_a \cdot z_{Pa} \right] \right.\right.$$

$$+ \sum_i \sum_j \left[E_{ij} \cdot L \cdot \left(c\_plan \cdot plan_{ija} + \sum_d \left(c\_inv\_f_d \cdot inv\_f_{ijd} \right) + c\_f \cdot f_{ija} \right) \right]$$

$$\left.\left. + \sum_S \left[c\_inv\_y_{Sa} \cdot inv\_y_{Sa} \right] \right) \right]$$

Subject to:

- Amount of produced CO_2 for every emitter
- Capacity constraint for each step of the CCTS chain
- Physical balance for infrastructure

Mathematical Problem: Constraints

Balance: $$\sum_i f_{ija} - \sum_i f_{jia} + \sum_P \left(match\_P_{Pj} \cdot x_{Pa} \right) - \sum_S \left(match\_S_{Sj} \cdot y_{Sa} \right) = 0$$

CO_2 – Balance: $$x_{p_a} + z_{p_a} = CO2_{p_a}$$

Capture: $$x_{Pa} \leq \sum_{b<a} \left(inv\_x_{Pb} \right)$$

Flow: $$f_{ija} \leq \sum_{b<a} \sum_d \left(cap\_d_d \cdot inv\_f_{ijdb} \right) + \sum_{b<a} \sum_d \left(cap\_d_d \cdot inv\_f_{jidb} \right)$$

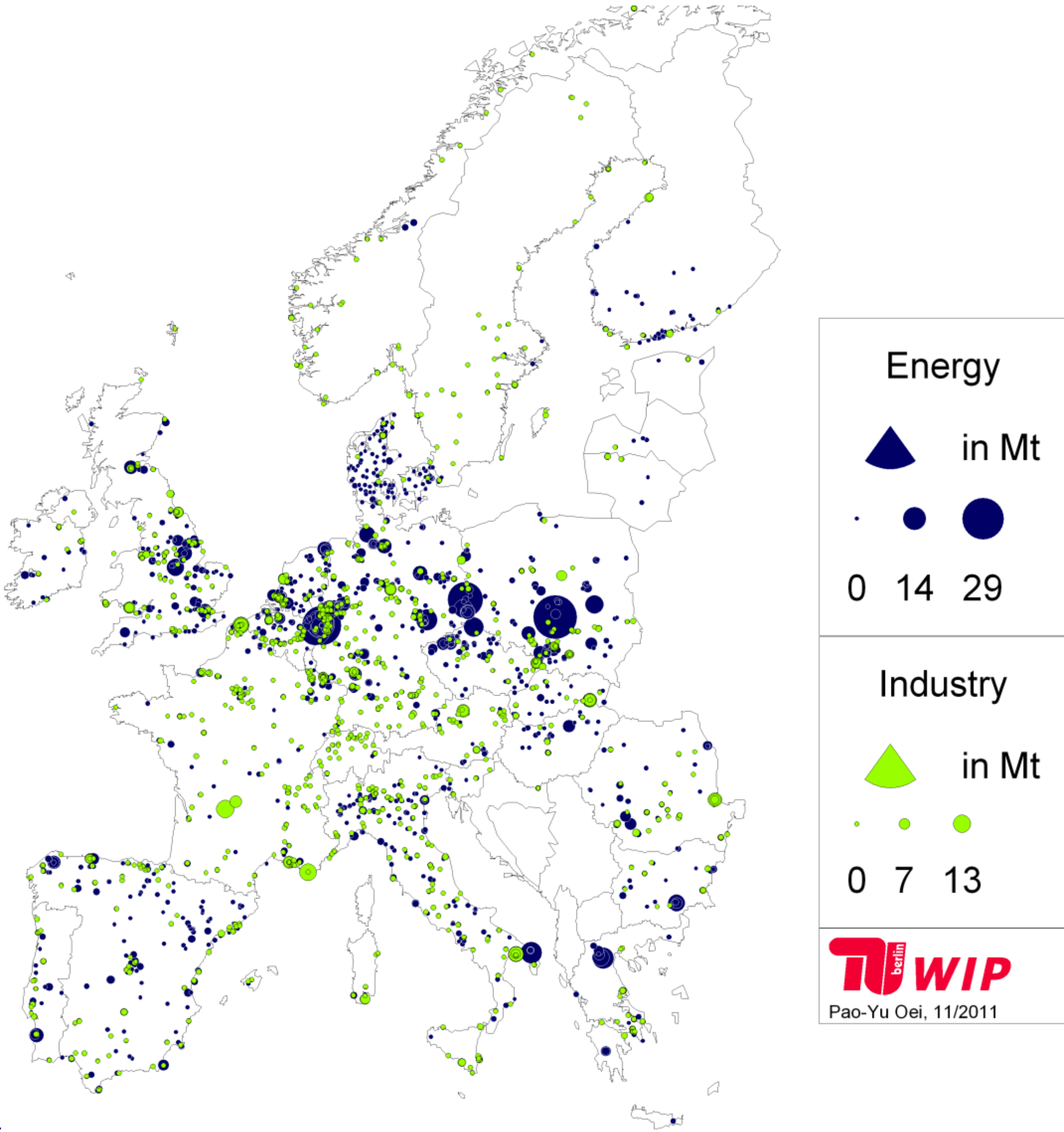
Storage: $$y_{Sa} \leq \sum_{b<a} inv\_y_{Sb}$$

Planning: $$\sum_d \left(inv\_f_{ijda} \right) \leq max\_pipe \cdot \sum_{b \leq a} \left(plan_{ijb} \right)$$

Total Storage: $$\sum_a y_{Sa} \leq cap\_stor_S$$

Non – Negativity: $$x_{Pa},\ inv\_x_{Pa},\ z_{Pa},\ f_{ija},\ y_{Sa},\ inv\_y_{Sa} \geq 0$$

Data: Sources in Europe

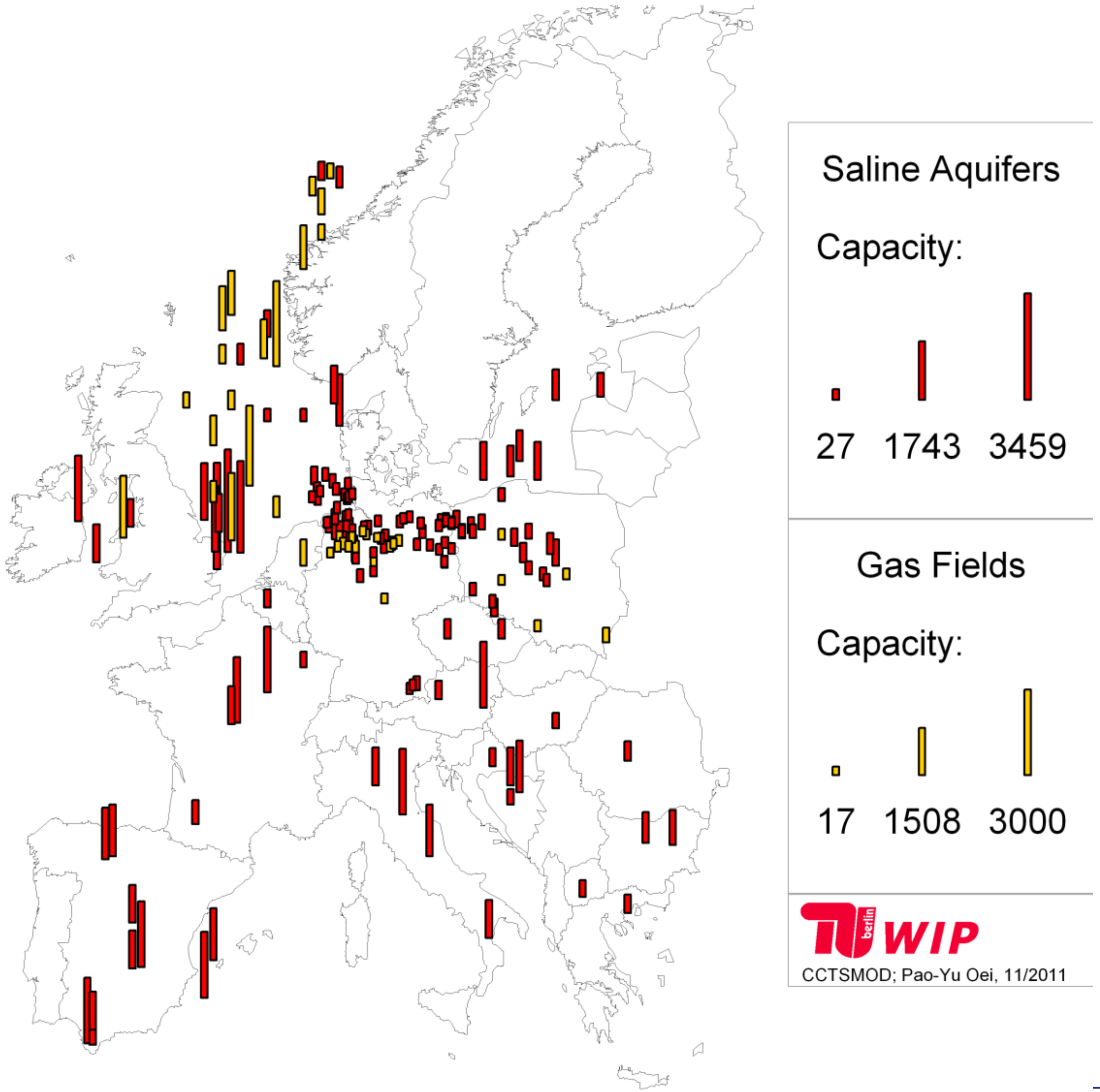


CO_2 source emissions

- 1618 fossil power
- 1847 heavy industry
- ~ 3.2 Gt CO_2 /a in 2010

Source: Own illustration

Data: Sinks in Europe

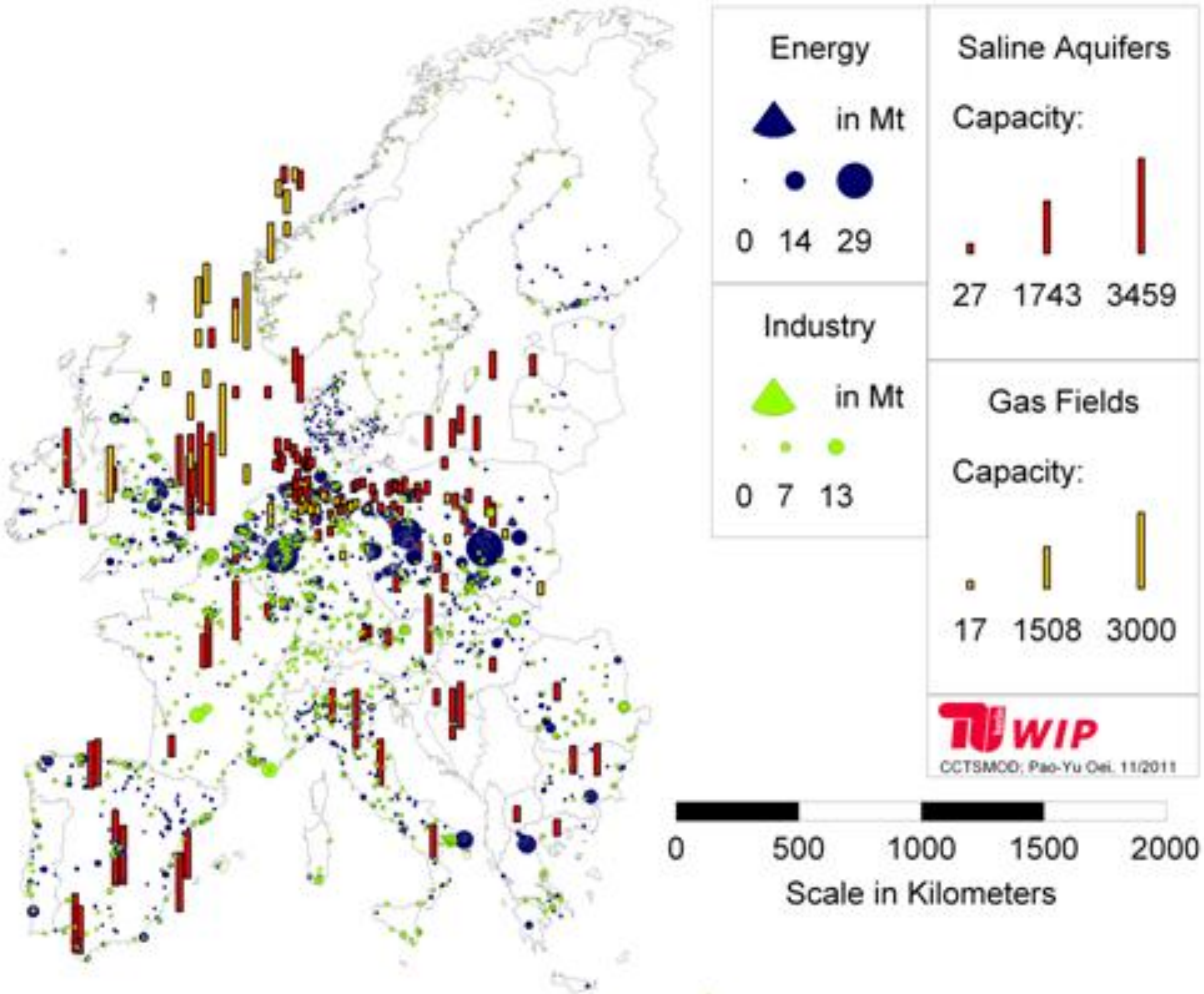


Available storage potential

- 44 Gt Onshore
- 50 Gt Offshore

Source: Own illustriation

Data: Sources and Sinks in Europe



CO_2 source emissions

- 1618 fossil power
- 1847 heavy industry
- ~ 3.2 Gt CO_2 /a in 2010

Available storage potential

- 44 Gt Onshore
- 50 Gt Offshore

Source: Own illustriation

Data: Capturing Costs

Variable Costs [€/tCO_2]	2010	2020	2030	2040	2050
Steam Coal	31,97	31,56	31,19	30,85	30,55
Gas	46,80	45,92	45,10	44,35	43,65
Lignite	29,35	29,06	28,81	28,58	28,37
Cement	16,89	16,89	16,89	16,89	16,89
Steel	16,39	16,39	16,39	16,39	16,39

Fixed Costs [€/tCO_2]	2010	2020	2030	2040	2050
Steam Coal	150	150	139	119	94
Gas	275	275	255	219	172
Lignite	116	116	108	92	73
Cement	135	135	125	107	84
Steel	117	117	109	93	73

Source: Own calculations based on Tzimas (2009) and WI (2008)

Uncertainties influencing deployment of CCTS

Available storage potential

- Low resolution data available to the public
- Different estimation methods

Development of the CO_2 certificate price

- CO_2 certificate price is driving force
- Price depends on future climate policies

Accessibility of storage sites

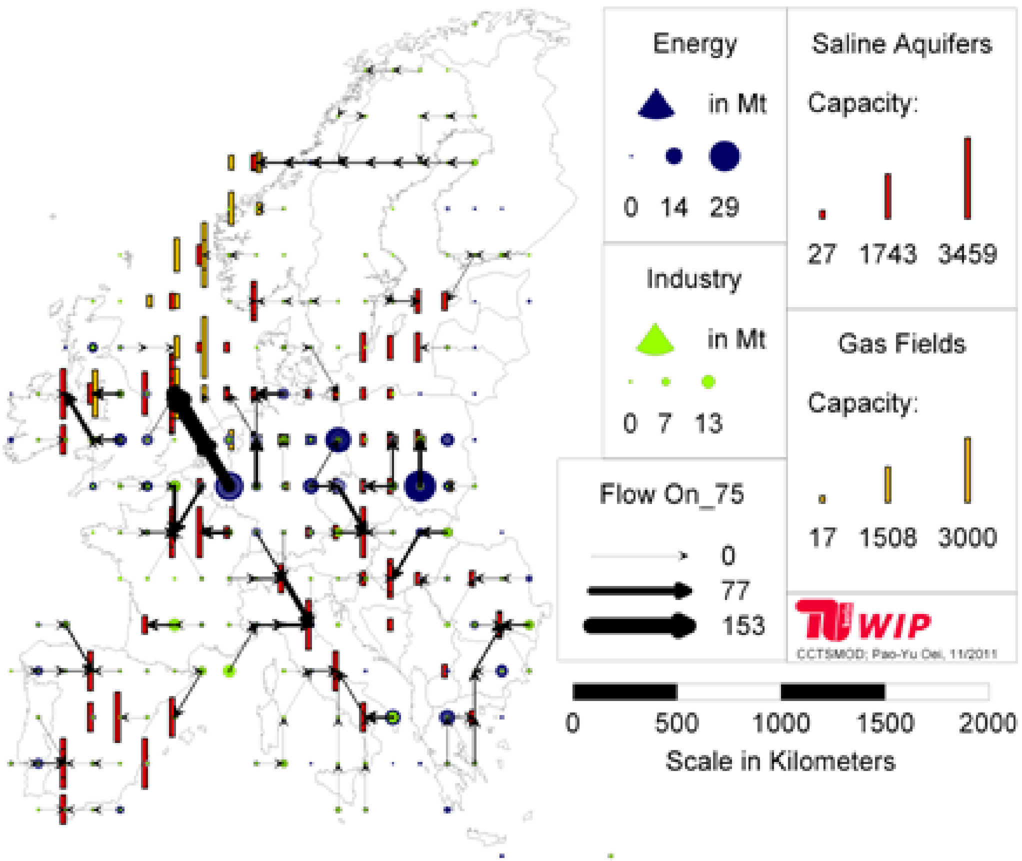
- Growing public resistance
- Offshore storage involves less stakeholders

Selected Scenarios

Scenario	CO_2 Certificate price in 2050	Public acceptance	Total Storage potential
BAU	75 Euro	Onshore & Offshore	94 Gt
Off 75	75 Euro	Offshore only	50 Gt
On 50	50 Euro	Onshore & Offshore	94 Gt
Off 50	50 Euro	Offshore only	50 Gt
On 100	100 Euro	Onshore & Offshore	94 Gt
Off 100	100 Euro	Offshore only	50 Gt

Scenario Results: BAU (Business as Usual)

in 2050



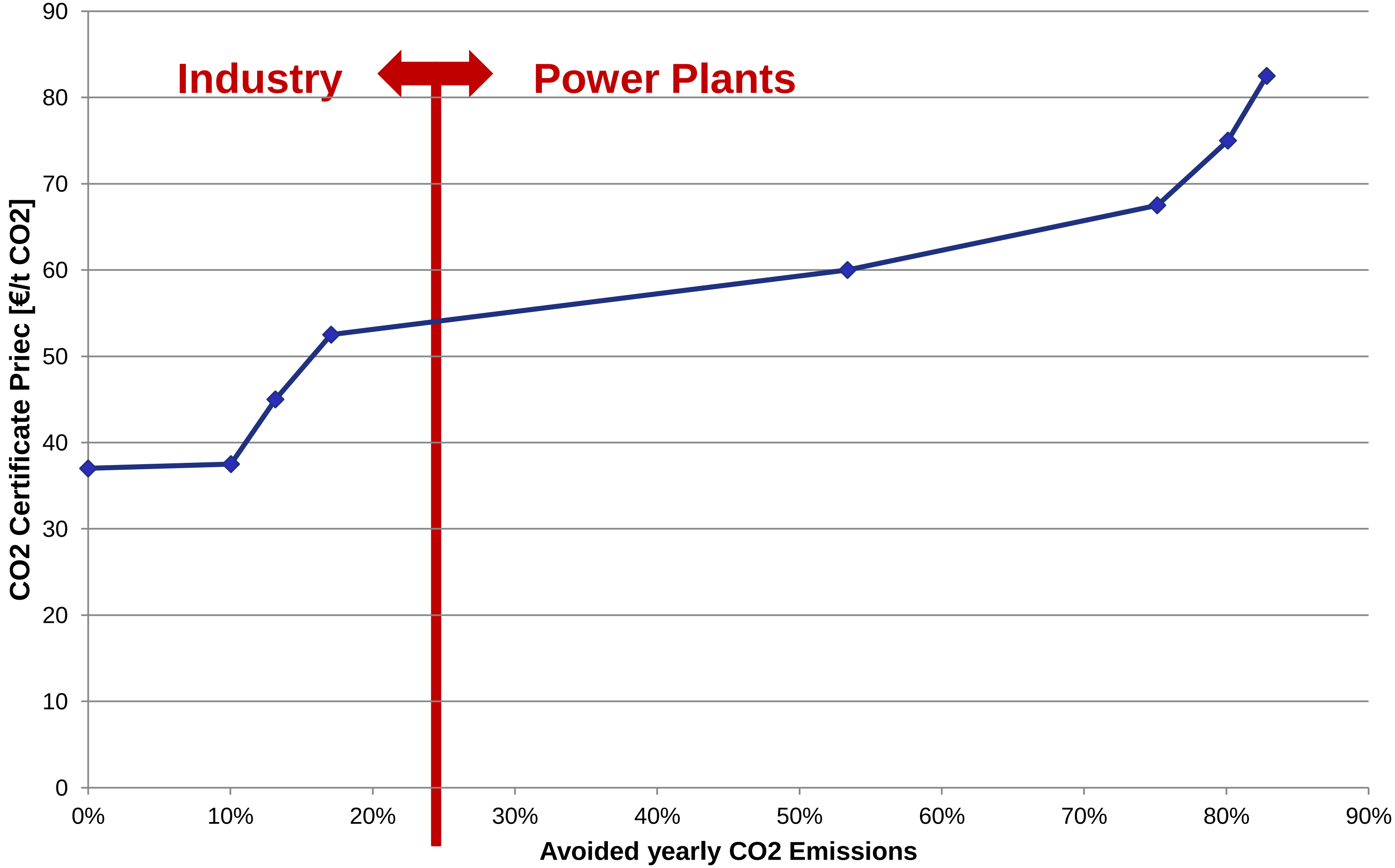
- Industry starts at 40 €/tCO2
- Coal starts at 55 €/tCO2
- 86 % of captured CO_2 is from the cement and iron/steel sectors

- Very important investment in pipeline network of 30,000 km needed
- 467 billion € investment costs
- 878 billion € variable costs over the complete time horizon

- 52 of 94 Gt storage left in 2050

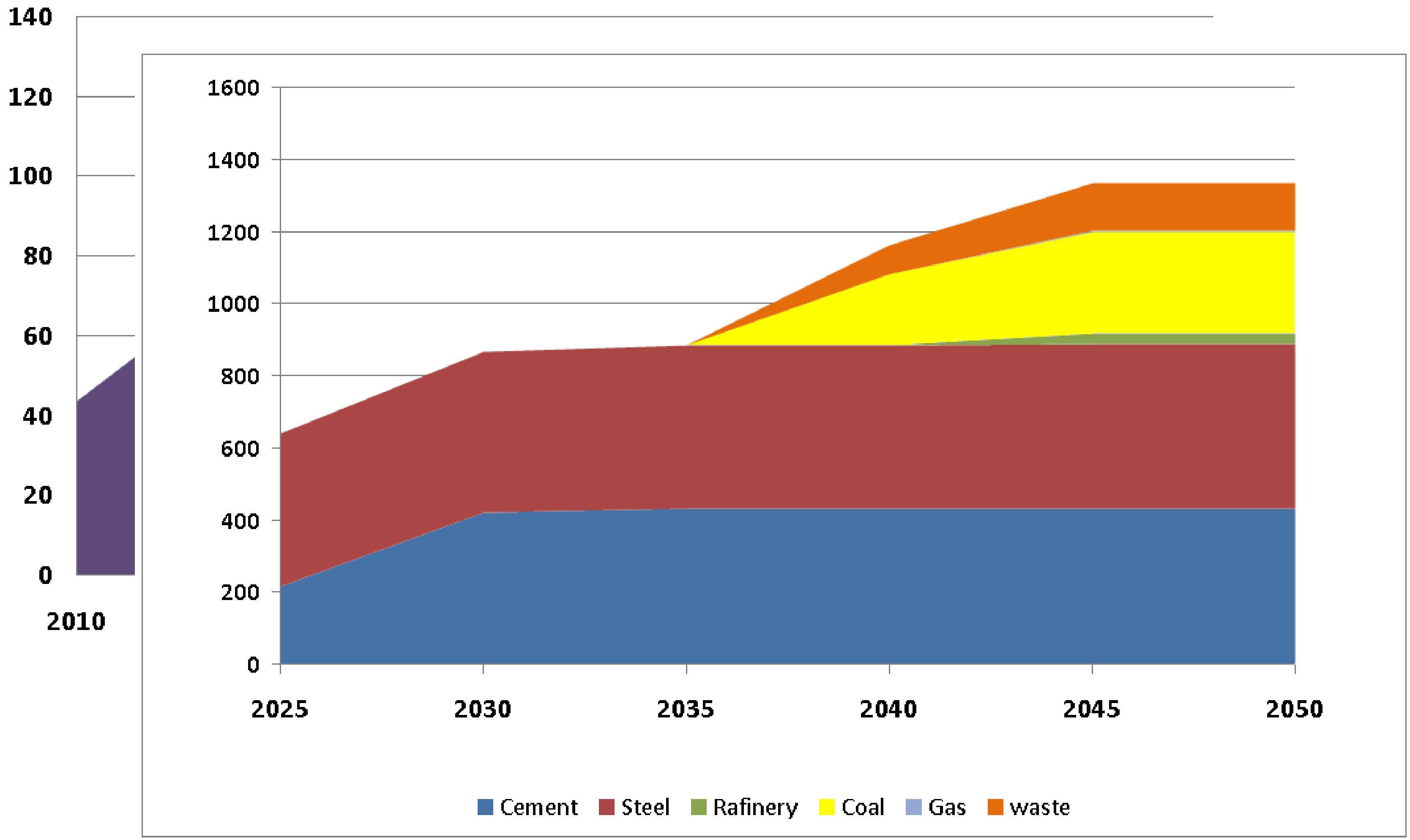
Source: Own illustriation

BAU: Costs for avoiding CO_2 emissions



Source: Own illustriation

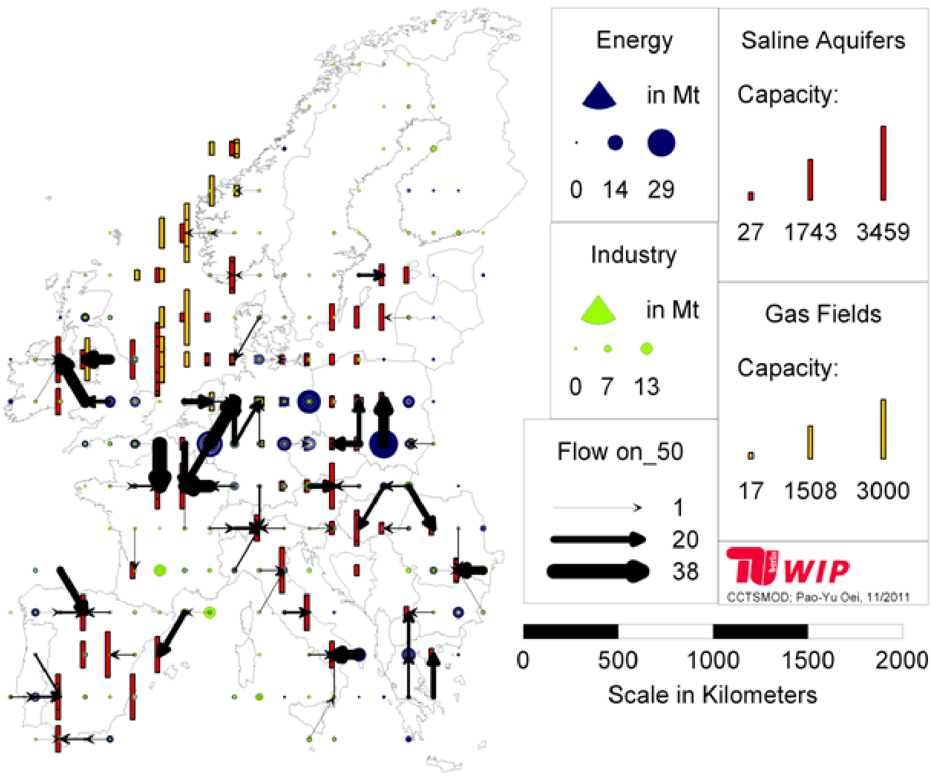
BAU: key figures



Source: Own illustriation

Scenario Results: Onshore 50

in 2050

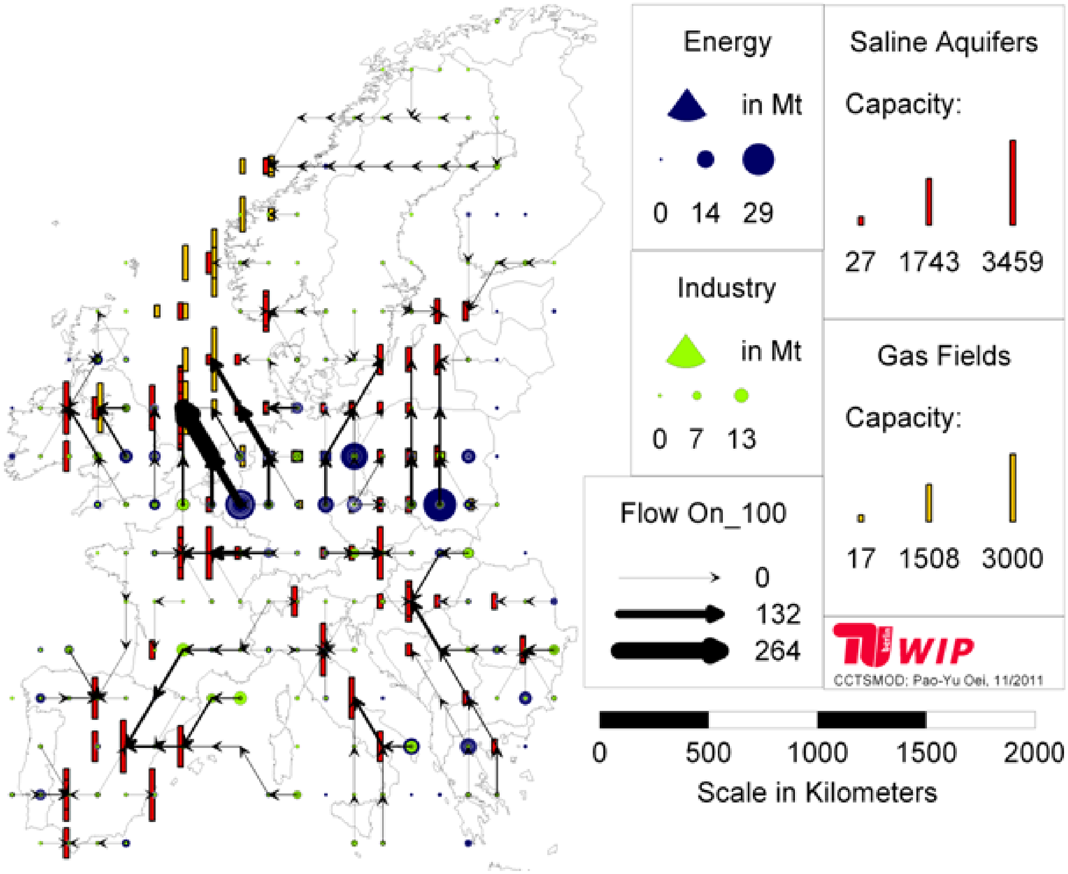


- 100 % of captured CO_2 is from the cement and iron/steel sectors
- Regional character of CCTS application
- Pipeline network of 17000 km needed
- 146 billion € investment costs
- 432 billion € variable costs
- 76 of 94 Gt storage left in 2050

Source: Own illustriation

Scenario Results: Onshore 100

in 2050



- Pipeline network of 33,000 km
- 413 billion € investment costs
- 1319 billion € variable costs
- 50 of 94 Gt storage left in 2050

→ scarcity of storage potential becomes visible (~ 25 years left)

Source: Own illustriation

Scenarios Results: Overview

Scenario	Share of stored industry Emissions	Pipeline Network [km]	Stored Emissions [$GtCO_2$]	Storage left in 2050 [$GtCO_2$]	CCTS investment costs [€bn]	CCTS variable costs [€bn]
BAU	86%	> 30,000	42	52	467	878
Off 75	82%	> 18,300	21	29	200	667
On 50	100%	> 17,000	18	76	146	432
Off 50	100%	> 9,500	7,7	42,5	127	203
On 100	88%	> 33,000	44	50	413	1319
Off 100	88%	> 57,000	41	9	417	1337

Conclusions I: Model Outcomes

- Industry first-mover, at CO_2 prices of 40€/t in 2050
- In industry, up to 80% reduction possible for reasonable prices (<50€/t)
- Energy sector needs prices above 55€/t to start CCTS investment

- Not enough affordable storage capacities for all European emitters, especially if only offshore storage possible

- CCTS especially for Northern Europe interesting
- Formation of regional clusters, interconnected pipeline network in the case of Offshore storage

Conclusions II: General Outcomes

- High abatement potential for industrial emissions (first mover)
  ➔ higher Network-Efficiency
- CCTS solution for unavoidable industrial CO_2 emissions
- Combined usage of industrial and electrical sector can lead to storage scarcity (esp. in offshore case)

- Transport does matters (5% – 7% of all costs onshore, 17% offshore), however only if the network is planned in an optimal way).

➔ Europe-wide infrastructure planning

Further Research

We are currently working on:

- Application of stochastic optimization
- Integration of Enhanced Oil Recovery (EOR)
- Further game theoretical applications

Thank you very much for your attention!

Are there any questions?

Selected References

GeoCapacity (2009): Assessing European Capacity for Geological Storage of Carbon Dioxide – The EU GeoCapacity Project. Energy Procedia, Volume 1, Issue 1, February 2009, Pages 2663-2670.

IEA (2009): Technology Roadmap – Carbon Capture and Storage. OECD, Paris, France: International Energy Agency.

Kobos et al (2007): The 'String of Pearls': The Integrated Assessment Cost and Source-Sink Model [Conference] // 6th Annual Carbon Capture & Sequestration Conference, May 7-10 2007. - Pittsburgh, USA : Sandia National Laboratories.

Mendelevitch, R., Oei, P.Y., Tissen, A. and Herold, J. (2010): CO_2- Highways – Modeling Aspects of a Future CO_2 Transport Infrastructure, Centre for European Policy Studies (CEPS), Working Document No. 340; Brussels, Belgium.

Middleton R. and Bielicki J.(2009): A Comprehensive Carbon Capture and Storage Infrastructure Model [Conference] // Proceedings of the 9th International Conference on Greenhouse Gas Technologies.

Oei, P.Y., Mendelevitch, R. Herold, J., Tissen, A. von Hirschhausen, C. (2010): CO_2-Autobahnen für Europa? Energiewirtschaftliche Tagesfragen (ET Magazin), Ausgabe 12/2010, ETV Energieverlag GmbH, Essen.

RECCS+ (2010): RECCS plus – Regenerative Energien (RE) im Vergleich mit CO_2-Abtrennung und Ablagerung (CCS) – Update und Erweiterung der RECCS-Studie. Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU).

Tzimas E. (2009): The Cost of Carbon Capture and Storage Demonstration Projects in Europe, European Commission, Joint Research Center, Institute of Energy.

Industrial CCTS Projects around the world

Project	*Country*	*Location*	*Capture Rate [tCO2/day]*
Prosint Methanol Production Plant	Brasil	Rio de Janeiro	90
Kurosaki Chemical Plant	Japan	Kurosaki	283
Sumitomo Chemicals Plant	Japan	Ichihara	150
Nippon Steel CO2 Capture Project	Japan	Kimitsu	170
Petronas Gas Processing	Malaysia	Kuala Lumpur	160
AES Shady Point	USA	Panama, Oklahoma	200
AES Warrior Run	USA	Cumberland, Maryland	123
American Electric Power - Mountaineer	USA	New Haven	274
Bellingham Cogeneration Facility	USA	Bellingham	335
Total Lacq (Oxyfuel)	France	Lacq	205

Capture Costs in Industry

Investment costs (based on Ho et al., 2010):

195 €/tCO_2 for iron and steel

225 €/tCO_2 for cement

325 €/tCO_2 for petrochemical

Variable costs (based on Ho et al., 2010):

17 €/tCO_2 for iron and steel (60% HC)

24 €/tCO_2 for cement (85% HC)

33 €/tCO_2 for petrochemical (115% HC)

Pipeline investment costs:

Onshore: 800.000 €/km, Offshore: 960.000 €/km for a diameter of 18`` (Alstom, 2011)

From 150.000 €/km to 1.200.000 €/km, depending on diameter (Metz et al., 2005)

Data: Costs for Reference and CCTS Power Plant

Technologie	Investitionskosten Demonstrationsprojekt in €$_{08}$/kW	Effizienz in %
Kohlestaubfeuerung	1478	46
Kohlestaubfeuerung mit Post-Combustion Abscheidung	2500	35
Integrated Gasification Combined Cycle (IGCC) mit CO2 Abscheidung	2700	35
Oxyfuel Carbon Capture	2900	35
Erdgas GUD Kraftwerk mit Post-Combustion Abscheidung	1300	46
Zementherstellung mit Post-Combustion Abscheidung	ca. 87% der Investitionskosten im Kraftwerksbereich	-
Kalkherstellung mit Post-Combustion Abscheidung	ca. 127 % der Investitionskosten im Kraftwerksbereich	-
Eisen- und Stahlherstellung mit Post-Combustion Abscheidung	ca. 61 % der Investitionskosten im Kraftwerksbereich	-

Source: Tzimas (2009), and Öko Institut (2011)

Mathematical Problem: Objective Function

$$\min_{\substack{inv\_x_{Pa},\, x_{Pa},\, z_{Pa},\, plan_{ija},\\ inv\_f_{ijda},\, f_{ija},\, inv\_y_{Sa}}} h = \sum_a \left[\left(\frac{1}{1+r} \right)^{(year_a - start)} \cdot \left(\sum_P \left[c\_inv\_x_P \cdot inv\_x_{Pa} + c\_ccs_{Pa} \cdot x_{Pa} + cert_a \cdot z_{Pa} \right] \right.\right.$$

$$+ \sum_i \sum_j \left[E_{ij} \cdot L \cdot \left(c\_plan \cdot plan_{ija} + \sum_d \left(c\_inv\_f_d \cdot inv\_f_{ijd} \right) + c\_f \cdot f_{ija} \right) \right]$$

$$\left.\left. + \sum_S \left[c\_inv\_y_{Sa} \cdot inv\_y_{Sa} \right] \right) \right]$$

Mathematical Problem: Constraints

Subject to:

$$x_{p_a} + z_{p_a} = CO2_{p_a} \quad (2)$$

$$x_{Pa} \leq \sum_{b<a} \left(inv\_x_{Pb} \right) \quad (3)$$

$$f_{ija} \leq \sum_{b<a} \sum_{d} \left(cap\_d_d \cdot inv\_f_{ijdb} \right) + \sum_{b<a} \sum_{d} \left(cap\_d_d \cdot inv\_f_{jidb} \right) \quad (4)$$

$$\sum_{d} \left(inv\_f_{ijda} \right) \leq max\_pipe \cdot \sum_{b \leq a} \left(plan_{ijb} \right) \quad (5)$$

$$\sum_{a} \left(5 \cdot y_{Sa} \right) \leq cap\_stor_S \quad (6)$$

$$y_{Sa} \leq \sum_{b<a} inv\_y_{Sb} \quad (7)$$

$$\sum_{i} f_{ija} - \sum_{i} f_{jia} + \sum_{P} \left(match\_P_{Pj} \cdot x_{Pa} \right) - \sum_{S} \left(match\_S_{Sj} \cdot y_{Sa} \right) = 0 \quad (8)$$

$$x_{Pa}, inv\_x_{Pa}, z_{Pa}, f_{ija}, y_{Sa}, inv\_y_{Sa} \geq 0 \quad (9)$$

$$plan_{ija} \in \{0,1\} \quad (10)$$

$$inv\_f_{ijda} \in N_0 \quad (11)$$

Mathematical Problem: Indices, Parameters and Variables

Indices

a, b	–	model period
P	–	individual CO_2 producer
S	–	individual CO_2 storage site
i, j	–	node
d	–	pipeline diameter [m]

Variables

h	–	net present value of total CO_2 abatement costs over the whole model time frame [€]
x_{Pa}	–	quantity of CO_2 captured by producer P in period a [t CO_2/a]
inv_x_{Pa}	–	investment in additional CO_2 capture capacity for producer P in period a [1]
z_{Pa}	–	quantity of CO_2 emitted into atmosphere by producer P in period a [t CO_2/a]
f_{ija}	–	CO_2 flow from node i to j in period a [t CO_2/a]
inv_f_{ijda}	–	investment in additional pipeline capacity with diameter d connecting nodes i and j in period a [1]
$plan_{ija}$	–	pipeline planning and development between nodes i and j in period a [1]
y_{Sa}	–	quantity of CO_2 stored per year in sink S in period a [t CO_2/a]

Parameters

r	–	rate of interest [%]
$year_a$	–	starting year of a model period a
$start$	–	starting year of the model
end	–	ending year of the model
c_ccs_{Pa}	–	variable costs of carbon capture for producer P in period a [€/t CO_2]
$c\_inv\_x_P$	–	investment costs of carbon capture for producer P [€/kw]
$CO2_{P_a}$	–	total quantity of CO_2 produced by producer P in period a [t CO_2]
$cert_a$	–	CO_2 Certificate price in period a [€/ t CO_2]
c_f	–	CO_2 flow costs [t CO_2]
$c\_inv\_f_d$	–	pipeline investment costs [€/km·m (diameter)]
c_plan	–	pipeline planning and development costs [€/km]
cap_d_d	–	capacity of a pipeline with diameter d [t CO_2/a]
max_pipe	–	max. number of pipelines built along planned route [1]
$c\_inv\_y_{Sa}$	–	investment costs for storage in sink S in period a [€/t CO_2]
cap_stor_S	–	storage capacity of sink S [t CO_2]
$match\_P_{Pj}$	–	mapping of producer P to node j
$match\_S_{Sj}$	–	mapping of Sink S to node j
E_{ij}	–	adjacent matrix of possible connections between nodes i and j