Using Real Options to Evaluate Optimal Funding Strategies for Carbon Capture, Transport and Storage Projects in the European Union

Jeremy M. Eckhause

Research Fellow, LMI

Ph.D. Candidate, Civil Systems, Department of Civil & Environmental Engineering, University of Maryland

Johannes Herold

Ph.D. Candidate, Workgroup for Infrastructure Policy (WIP), Berlin University of Technology (TU Berlin)

5th Trans-Atlantic INFRADAY 2010

Resources for the Future, Washington, DC

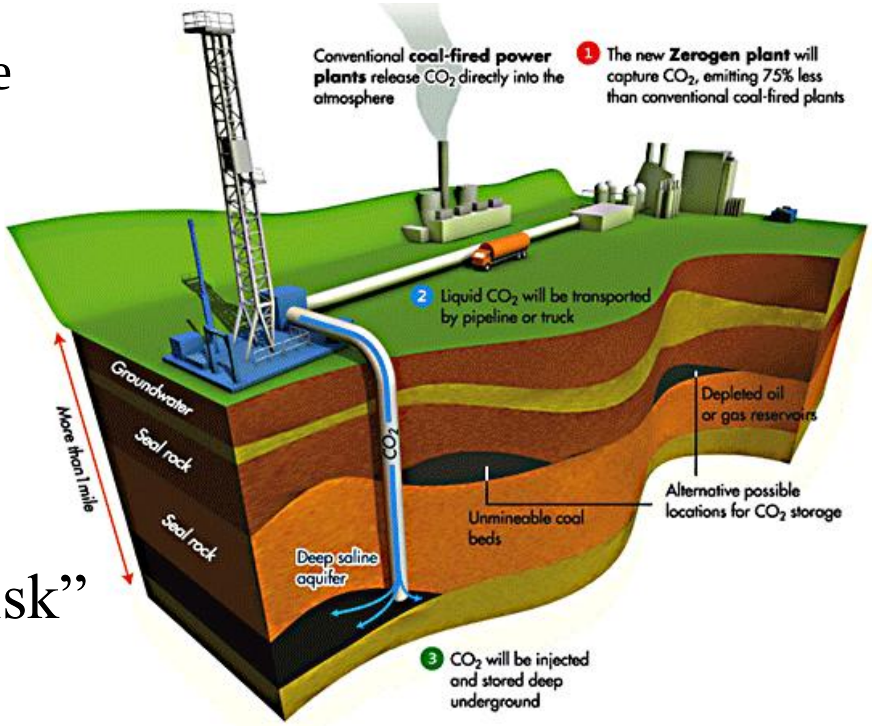
November 11, 2011

Outline

- Description of CCS projects in the European Union
- Description of state transition probabilities and costs
- Real options formulation for this problem
  - Modeling it as a multi-project, multi-project competition
- Solution results under different budgets (and budget allocations) for:
  - Pre-Combustion projects
  - Post-Combustion and Oxyfuel projects
- Results for knowledge spillover cases
- Conclusions and acknowledgements

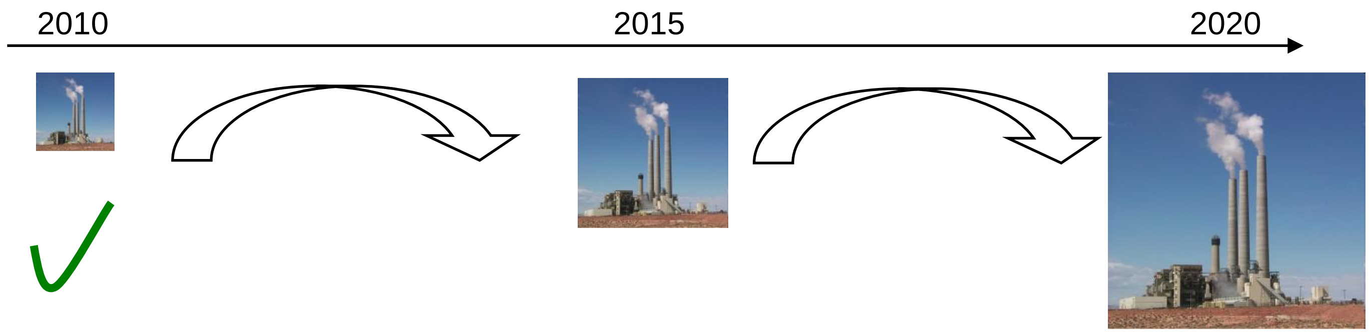
Carbon Capture and Storage

- CO_2 emissions from large point sources are captured, compressed, transported and stored underground.
- Three technology options:
  - Post- and
  - Pre-combustion capture
  - Oxyfuel process
- Pre- and post-comb. capture are proven technologies on small and medium scale.
- Innovative oxyfuel plants considered "higher costs, higher risk" projects.



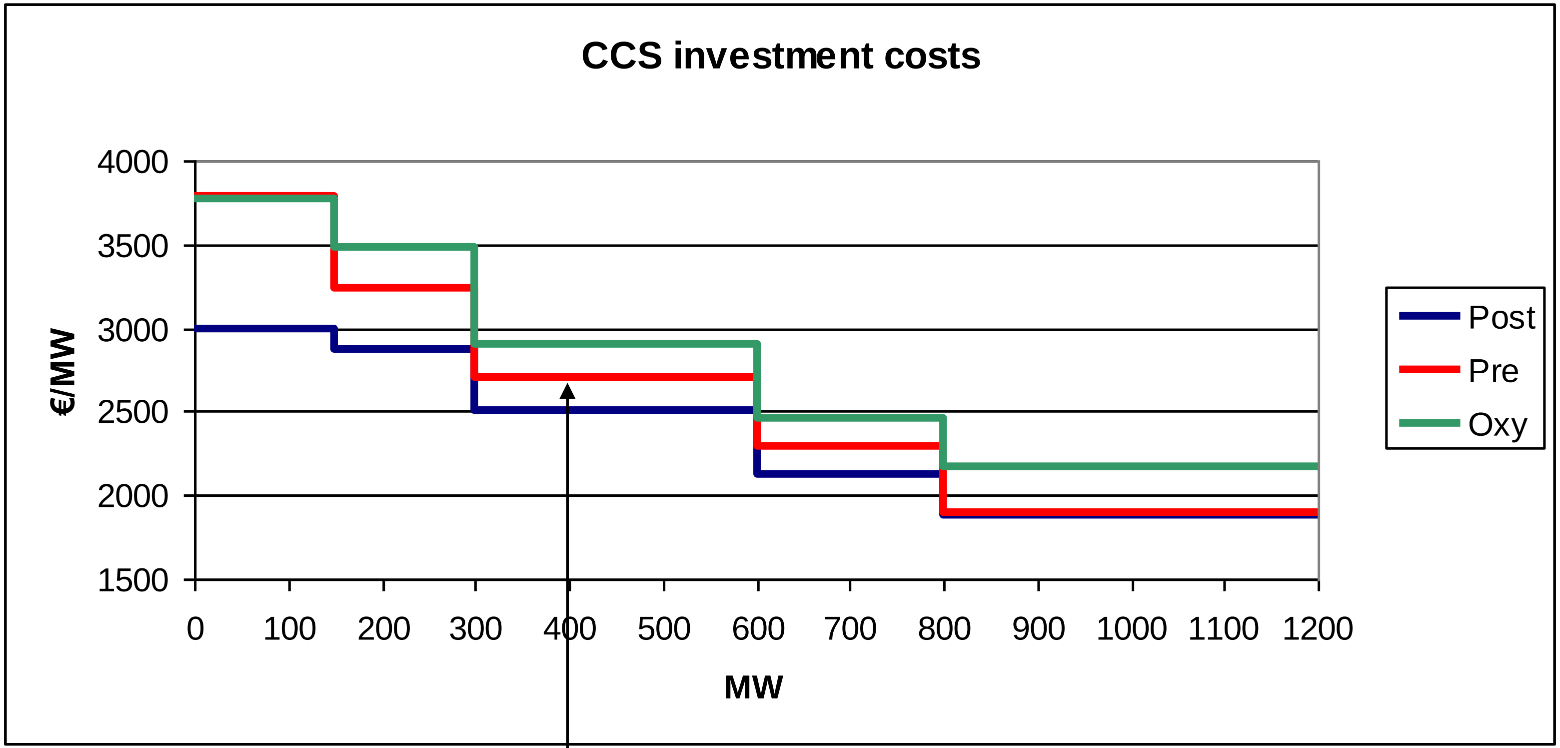
CCS Projects in the EU

- The first CCS (30 MW oxy-fuel) pilot project started operation in Germany in 2008.
- Demonstration projects (<300MW) planned in different EU member states by various companies through 2015.
- Full scale oxyfuel power plants (~1GW) should be operating by 2020.



- Due to high costs and high risk of technology failure, public funding is needed to get the technology working at large-scale by 2022.
- Project success probabilities depend on public funding decisions and the state of the project and competing projects.

Project Costs and Transition Probabilities



Based on literature review (Tzimas, 2009)

Project Costs and Transition Probabilities

- Experts gave their opinion for the technology success probability assuming a 500 MW plant.
- In a next step, those success probabilities were adjusted according to the plant size and the potential budget.

Success probability of the first project staying within the budget

	0 – 150 MW	150 - 300 MW	300 - 600 MW	600 - 800 MW	800 - 1200 MW
Post-combustion	100%	86%	75%	68%	60%
Pre-combustion	81%	69%	58%	46%	41%
Oxyfuel	98%	81%	68%	54%	48%

Technology success probability of the first project subject to changes in the budget

	- 20%	- 10%	500 MW	+ 10%	+ 20%
Post-combustion	65%	68%	75%	80%	85%
Pre-combustion	46%	50%	58	62%	66%
Oxyfuel	55%	59%	68	73%	77%

Other Cost and Probability Parameters

- If previous stage was successfully undertaken within a project, the success probability for the following stage increases by 20%.
- There are early innovators for each technology. These have a 5% higher success probability on each stage:
  - Oxy-Fuel: Vattenfall
  - Pre-Combustion: RWE
  - Post-Combustion: E.ON
- There may be cross-technology learning (knowledge spillover) between post-combustion and oxy-fuel projects. This lowers the investment costs of the plants:

	Post-combustion	Pre-combustion	Oxyfuel
Post-combustion	- 8%	0%	- 3%
Pre-combustion	0%	- 8%	0%
Oxyfuel	- 3%	0%	- 8%

CCS Projects Considered

- 8 Projects in Total
  - 2 Oxyfuel
  - 3 Post-Combustion
  - 3 Pre-Combustion

Project	Unit Size [MW]			Expected Start of Operation		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Oxy 1	30	300	1000	2008	2014	2018
Oxy 2	30	320	-	2012	2016	-
Post 1	-	250	-	-	2014	-
Post 2	-	450	900	-	2014	2018
Post 3	-	250	-	-	2016	-
Pre 1	-	450	-	-	2014	-
Pre 2	-	900 IGCC	300 PCC	-	2014	2016
Pre 3	-	1200 IGCC	900 PCC	-	2012	2014

  - PCC: Pre-Combustion Capture

Technology State Definition

State (2, 1, 0, 0, 0)

Project stage:

1 = Pilot stage
2 = Demonstration stage
3 = Full-Scale project

Operation phase:

1 = Construction
2 = Proven

Third party project:

0 = No third party operating
1 = Oxyfuel project operating
2 = Post-comb project operating
3 = Pre-comb project operating
4 = post and oxy operating

Construction started:

0 = four years earlier
1 = six years earlier
2 = eight years earlier

Previous stage:

0 = not undertaken
1 = success

Affects cases where knowledge spillover occurs

- Full success is defined as reaching State (3,2,-,-,-)

Overview of CCS Real Options Problem

Central Questions:

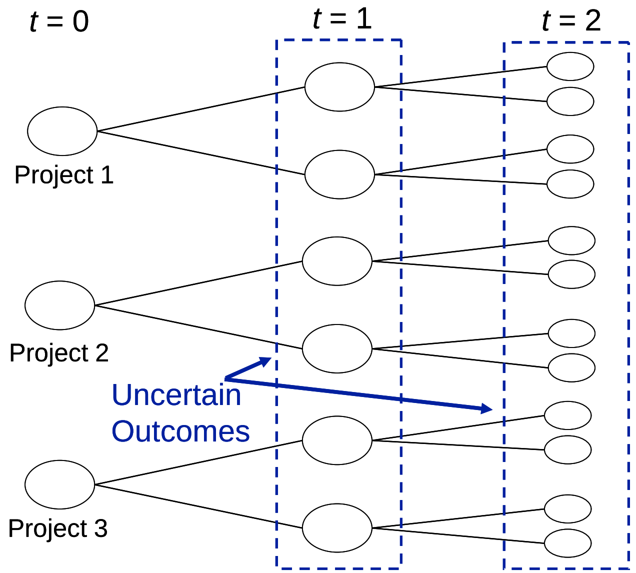
- From the EU's perspective, how should they fund R&D in these CCS projects for power generation?
- Need to consider that there is limited investment capital.
- Different objective functions possible:
  - Maximize probability of a fully functioning CCS plant by 2022
  - Multi-objective function that considers above objective with additional technology aspects such as CO_2 storage or transport.
  - etc.
- **Our objective function**: *Maximize probability of a fully functioning CCS plant by 2022 under two cases*:
  - Pre-Combustion projects
  - Post-Combustion and Oxyfuel projects
- This is essentially a real options problem that considers R&D investment under uncertainty.

A Real Options Approach for CCS Funding

- Consider the problem as a multi-stage, multi-project competition ideal problem for a real options framework:
  - Each stage represents a decision time period (here, 2 years)
  - The cost of exercising each option is the amount of funding required for each project's development
  - An option is exercised through the award of a continuation of funding.

- Solution is the optimal portfolio of options (energy projects) to fund at each stage to maximize overall capability success.
- Can use stochastic dynamic programming to solve.
- We use the transition probabilities:

$$\mathbf{P}[s_{it+1} = s \mid S_t, X_{itl} = 1]$$



CCS Real Options Problem: Possible Budget Allocations

How can budgets be allocated?

- Case 1: Each time period the decision-maker has a fixed budget available
  - For example, 400 million Euros each of the six time periods: (400, 400, 400, 400, 400, 400)
- Case 2: The total budget is flexible, and is spent as needed
  - Begin first time period with 400x6 = 2400 million Euros, and determine how much to spend optimally at each time period
    - This offers the most flexibility to the decision-maker.
- Case 3: Each time period's budget is optimized
  - For example, can allocate budget as (600, 300, 300, 600, 200, 400) among the six time periods, if that is optimal
  - Eckhause, *et al*. (2011): solving as an integer program for Case 3 can be faster for problems of a certain size.

$$z^*_{\text{Case1}} \leq z^*_{\text{Case3}} \leq z^*_{\text{Case2}}$$

Applying Real Options to CCS Funding Decisions: Fixed Budget (Case 1)

Suppose the budget amount for every stage is fixed.

- Let $s_{it} \in S$ be the state of project i at time period t. State of all projects at time t is S_t
- $s_{\text{full}} \in S$ is the state representing a successfully operating full-scale CCS plant.
- Let $X_{itl} \in \{0,1\}$ be the decision variable of whether to fund project i at time period t at level l
- Let c_{itlS_t} represent the cost of funding project i at level l in time period t, given that the state of the system is S_t
- Let B_t represent the budget available for time period t

We solve for:

$$X(S_t) = \begin{cases} (X_t) \in \{0,1\}^{I \times L} : \sum_{i,l} c_{itlS_t} X_{itl} \le B_t \\ \sum_{l \in L} X_{itl} \le 1 \quad \forall\, i \in I \end{cases}$$

So that

$$V_t(S_t) = \max_{X_t \in X(S_t)} \mathbf{E}\{V_{t+1}(S_{t+1}) \mid S_t, X_t\} \quad t = 1, \ldots, T$$

Where:

$$V_{T+1}(S_{T+1}) = \begin{cases} 1 & \text{if} \quad s_{i,T+1} = s_{\text{full}} \quad \text{for some project } i \\ 0 & \text{otherwise} \end{cases}$$

Extending the Problem: Flexible Budget (Case 2)

Extending the formulation to a flexible budget (Case 2):

- Total budget for all periods B_1 can be spread budget between each phase
  - B_t denotes budget *remaining* at time period *t*: $B_{t+1} = B_t - \sum_{i,l} c_{itlS_t} X_{itl}$
  - Boundary condition:

$$V_t(S_t, B_t) = \max_{(X_t, B_{t+1}) \in X(S_t, B_t)} \mathbf{E}\{V_{t+1}(S_{t+1}, B_{t+1}) \mid S_t, X_t\} \quad t = 1, \ldots, T$$

- Must discretize budget between periods.
  - Value for budget increment can be between 1-10 million Euros.
- The run-times and state variables for the flexible-budget problems span:

CCS Projects	With Spillover?	Budget Increment (€ Million)	State Variables (Each Period)	State Variables (Total)	Run-Time (CPU Sec.)
Pre-Combustion	No	1	353,700	2,122,200	8
Post-Combustion & Oxyfuel	No	1	940,800	5,644,800	46
Pre-Combustion	Yes	1	2,122,200	12,733,200	63
Post-Combustion & Oxyfuel	Yes	10	23,708,160	142,248,960	974

Extending Further: Budget-Optimal (Case 3)

Extending the formulation to a specified, but optimized, budget for each time period.

- Must solve this problem as a two-level SDP where
  - the upper level problem is "all possible" budget allocations
  - the lower-level problem is an optimal solution for a fixed-budget allocation
- Scenario-reduction heuristics were employed. The run-times and number of lower-level problems for the budget-optimal problem:

Pre-Comb

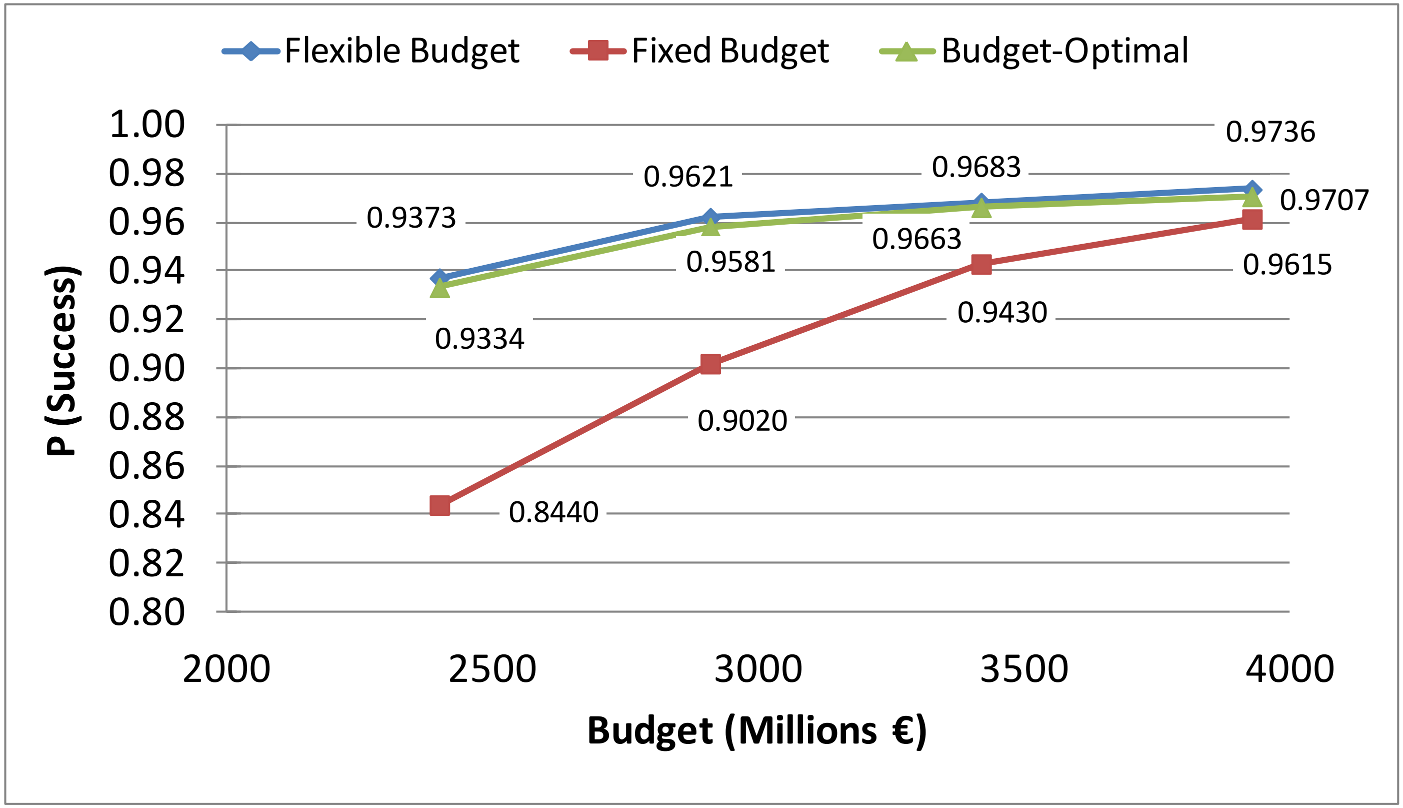
Total Budget	600 [m €]	1200 [m €]	1800 [m €]	2400 [m €]	2910 [m €]	3420 [m €]	3930 [m €]
Run-Time (sec)	22	514	201	851	1,873	386	558
Lower-Level SDPs	710	24,376	8,708	38,608	73,922	16,815	20,518

Post-Comb & Oxyfuel

Total Budget	600 [m €]	1200 [m €]	1800 [m €]	2100 [m €]	2400 [m €]	4800 [m €]
Run-Time (sec)	2	19	205	119	157	1,828
Lower-Level SDPs	156	5,947	75,813	40,332	55,471	607,474

Results: Pre-Combustion Projects

- For the Pre-Combustion projects, we get the following probability of success as a function of overall budget



Fixed-Budget vs. Budget-Optimal Solutions

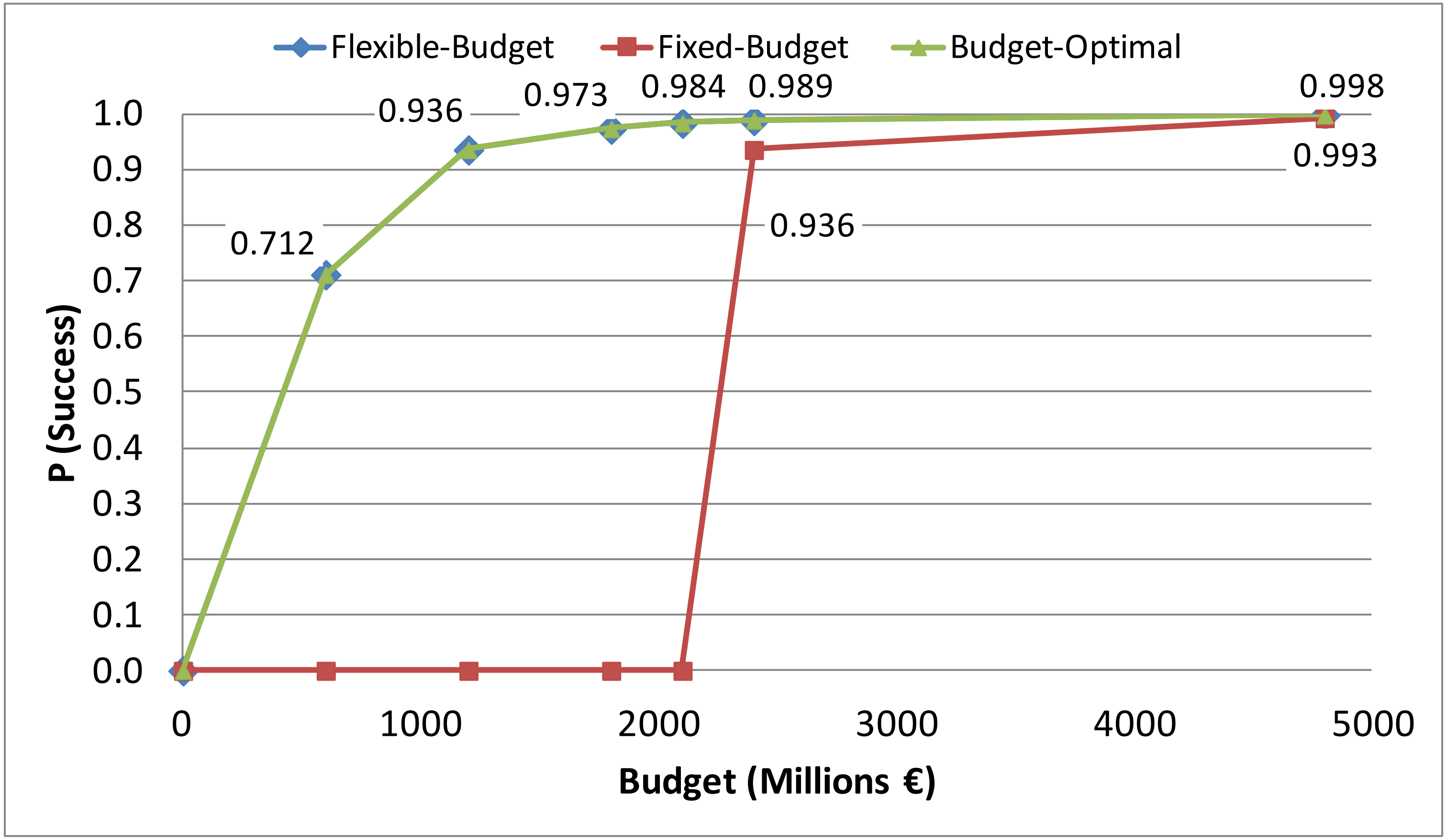
- For the Pre-Combustion CCS projects, the objective functions' values (probability of success) depend greatly on the budget allocation scheme.

Period	Budget [m €]	Budget [m €]	Budget [m €]	Budget [m €]	Budget [m €]	Budget [m €]
1 (2010)	200	300	400	910	910	910
2 (2012)	200	300	400	400	910	910
3 (2014)	200	300	400	400	400	910
4 (2016)	200	300	400	400	400	400
5 (2018)	200	300	400	400	400	400
6 (2020)	200	300	400	400	400	400
Total Budget	**1200**	**1800**	**2400**	**2910**	**3420**	**3930**
Fixed-Budget Objective	**0.000**	**0.000**	**0.844**	**0.902**	**0.943**	**0.962**

Period	Budget [m €]	Budget [m €]	Budget [m €]	Budget [m €]	Budget [m €]	Budget [m €]
1 (2010)	324	732	732	732	1056	1056
2 (2012)	0	0	423	423	423	423
3 (2014)	345	324	423	747	747	1140
4 (2016)	345	324	324	423	648	747
5 (2018)	84	324	324	423	423	423
6 (2020)	102	96	174	162	123	141
Total Budget	**1200**	**1800**	**2400**	**2910**	**3420**	**3930**
Budget-Optimal Objective	**0.779**	**0.889**	**0.933**	**0.958**	**0.966**	**0.971**

Results: Post-Combustion and Oxyfuel Projects

- For the Post-Combustion and Oxyfuel Projects, the budget allocation case greatly affects the solution



CCS Real Options Results: Knowledge Spillover

- Based on our assumptions about the effects knowledge spillover, the results varied little for both sets of technologies

Pre-Comb

Budget [m €]	Fixed-Budget Problems: No Spillover (A)	Fixed-Budget Problems: Knowledge Spillover (B)	Fixed-Budget Problems: Increase (B-A)	Flexible-Budget Problems: No Spillover (A)	Flexible-Budget Problems: Knowledge Spillover (B)	Flexible-Budget Problems: Increase (B-A)
0	0	0	0	0	0	0
600	0	0	0	0.405	0.405	0
1200	0	0	0	0.781	0.781	<0.001
1800	0	0	0	0.903	0.903	0.001
2400	0.844	0.844	0	0.937	0.938	0.001
2910	0.902	0.903	<0.001	0.962	0.963	0.001
3420	0.943	0.944	0.001	0.968	0.969	0.001
3930	0.962	0.963	0.001	0.974	0.975	0.001

Post-Comb & Oxyfuel

Budget [m €]	Fixed-Budget Problems: No Spillover (A)	Fixed-Budget Problems: Knowledge Spillover (B)	Fixed-Budget Problems: Increase (B-A)	Flexible-Budget Problems: No Spillover (A)	Flexible-Budget Problems: Knowledge Spillover (B)	Flexible-Budget Problems: Increase (B-A)
0	0	0	0	0	0	0
600	0	0	0	0.712	0.712	0
1200	0	0	0	0.936	0.936	0
1800	0	0	0	0.973	0.974	0.001
2100	0	0.720	0.720	0.984	0.984	0.000
2400	0.936	0.936	<0.001	0.989	0.990	0.001
4800	0.993	0.993	<0.001	0.998	0.999	<0.001

Summary and Conclusions

- This real options approach allows for a more quantitative risk mitigation for the funding of CCS projects in the EU.
  - Approach can easily be extended to other funding scenarios and objective functions.
- Budget allocation can greatly affect the probability of project success
  - It is important to identify how success probabilities change with funding levels, as the outcomes are greatly dependent upon it.
- A natural conflict between the risk-minimizing CCS portfolio strategy from the perspective of the funding agency and the necessity for a credible funding strategy from the perspective of the firms
- Budget-optimal allocation leads to objective function values very close to the fully flexibly budget allocation.
  - The advantage of the budget-optimal allocation over the flexible allocation is an increase in the credibility of the funding scheme from the perspective of the firms undertaking such high risk projects.

Acknowledgements and Bibliography

- We would like to thank the following for their estimates of the costs and success probabilities for the CCS projects in this presentation:
  - Dr. Joachim Geske, Dr. Peter Markewitz, and Dr. Stefan Vögele from Forschungszentrum Jülich
  - Mr. Michael Trompelt of Technische Universität Bergakademie Freiberg
  - Two anonymous experts

- Bibliography

  - Eckhause, J.M., and Herold, J. (2011). "Using Real Options to Evaluate Optimal Funding Strategies for Carbon Capture, Transport and Storage (CCS) Projects in the European Union," Under Review.
  - Eckhause, J.M., Gabriel, S.A., and Hughes, D.R. (2011). "An Integer Programming Approach for Evaluating R&D Funding Decisions with Optimal Budget Allocations," *IEEE Transactions on Engineering Management*, Forthcoming.
  - Eckhause, J.M., Hughes, D.R., and Gabriel, S.A. (2009). "Evaluating Real Options for Mitigating Technical Risk in Public Sector R&D Acquisitions," *International Journal of Project Management*, 27(4): 365-377.