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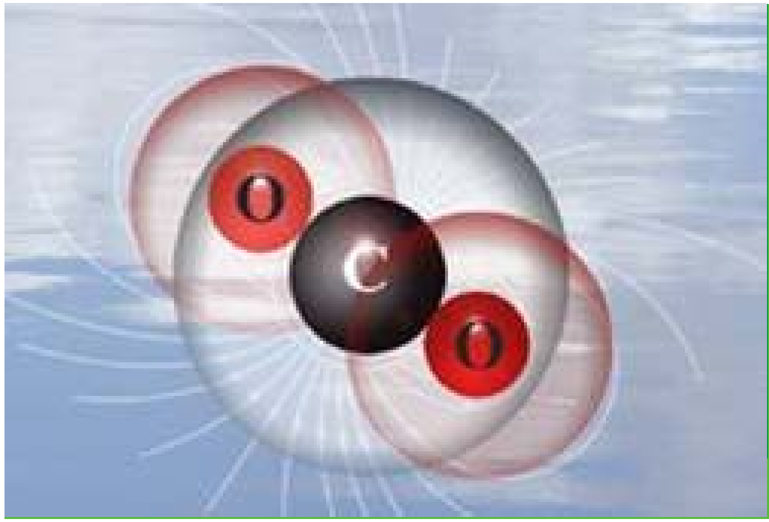

Modeling the Diffusion of Carbon Capture and Storage under Emission Control and Technology Learning

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Chair of Energy Economics and Public Sector Management

Agenda

1. **Innovation in Energy Technologies**
2. **Concept of Technology Learning**
3. **The Model**
4. **Scenarios and Results**
5. **Conclusion**
6. **Literature**

Innovation in Energy Technology

- **CCS, on and off-shore wind are considered as the most important low-carbon energy technologies for the German market**
- **Under today's emission restrictions, electricity producers miss economic incentives to apply CCS or other innovative high cost energy technologies**
- **No early bird market as in consumer electronics, high knowledge spillovers**
- **But innovative technologies often have a high potential for improvement**
- **The higher generation costs of CCS electricity are assumed to decline over time through learning <u>effects if the technology is applied</u>**

- **We therefore develop an economic, dynamic model to simulate the diffusion of CCS technology and wind under the German base-load regime, while taking into account expected learning effects**
- **CCS and wind are often referred to as being competitors to each other, focusing on one might harm the other.**

Introduction to Technology Learning

- **First observed by Wright (1936) in airplane manufacture as decreasing labor time requirements as workers gained experience with a certain task**
- **A more comprehensive analysis by the Boston Consulting Group found learning rates between 10 to 25% along industries, each time cumulative output doubles**

$$C_t = a * CC_t^{-b}$$

$$a = \frac{C_0}{CC_0^{-b}}$$

$$C_t = \text{technology cost in t}$$

$$CC_t = \text{Cumulated installed Capacity in t}$$

$$b = \text{learning exponent}$$

- **Study by Rubin et al (2006) indicates that the learning rate for CCS power plants capital costs could be expected around 10%**
- **However, we found no data on expected plants efficiency improvement, which is accounted for in the model**

The Model

- **Diffusion of CCS is modeled in a perfectly competitive market, in which the producer chooses a welfare maximizing production portfolio of different generation technologies**
- **Available technologies are: nuclear, lignite, natural gas combined cycle, wind on- and off-shore and lignite CCS**
- **Each technology is characterized by specific capital costs, efficiency, plant life and CO_2 emission per MWh_{el}, which are limited**
- **In case of CCS, this leads to an emission reduction of 80% compared to the standard technology.**

Model Formulation

- **Player faces a linear inverse demand function of the form:**

$$P_t = \frac{a_t - D_t}{b_t}$$

$$\sum_{g\tau \le t} X_{g,\tau,t} = D_t = a_t - b_t P_t$$

$$X_{g,\tau,t} = \text{Plants production of technology g in t installed in } \tau$$

$$fl_{g,\tau,t} * CAP_{g,\tau} + flex_{g,\tau,t} * excap_{g,\tau} \ge X_{g,\tau,t}$$

$$fl_{g,\tau,t} = \text{age dependent fullload hours}$$

$$CAP_{g,\tau} = \text{avaiable capacity of technology g installed in } \tau$$

$$flex_{g,\tau,t} * excap_{g,\tau} = \text{exogenous capacity}$$

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Model Formulation

- **Capacity depreciation modeled as decreasing availability of plants**

$$fl_{\tau,t} \begin{pmatrix} 0{,}95 & 0{,}91 & 0{,}86 & 0{,}81 & 0{,}75 & 0{,}69 & 0 & 0 \\ & 0{,}95 & 0{,}91 & 0{,}86 & 0{,}81 & 0{,}75 & 0{,}69 & 0 \\ & & 0{,}95 & 0{,}91 & 0{,}86 & 0{,}81 & 0{,}75 & 0{,}69 \\ & & & 0{,}95 & 0{,}91 & 0{,}86 & 0{,}81 & 0{,}75 \end{pmatrix}$$

$$CAP_{g,(t+ilag_g)} = ICAP_{g,t}$$

$$ICAP_{g,t} = \text{investment into new capacity}$$

$$imax_g \geq ICAP_{g,t}$$

$$imax_g = \text{investment constraint}$$

Model Formulation

$$E_{g,t} = \sum_{\tau, f(g,f) \in M} (1 - cpr_{g,\tau}) * \frac{\theta_f}{\eta_{g,\tau}} * X_{g,\tau,t}$$

$E_{g,t}$ = Emissions of plant using technology g

$cpr_{g,t}$ = Emission capture rate of technology g

θ_f = carbon emission factor of fuel f

$$e\max_t \geq \sum_g E_{g,t}$$

$e\max_t$ = exogenous emission restriction

Modeling of Learning

$$PI_{g,t} = pi_{g,0} * \left(\frac{cap_{g,0}}{cap_{g,0} + \sum_{\tau < t} ICAP_{g,\tau}} \right)^{-\alpha_g}$$

$$\alpha_{CCS} = 0.1$$

$$\eta_{g,t} = \eta_{g,0} * \left(\frac{gen_{g,0}}{gen_{g,0} + \sum_{\bar{\tau} < t, \tau < \bar{\tau}} X_{g,\tau,\bar{\tau}}} \right)^{-\gamma_g}$$

$$\gamma_{CCS} = -0.025$$

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Model Formulation

- **We maximize sum of future discounted welfare**
- **Welfare is calculated as the integral under the demand curve less the production cost which consist of fuel and other variable cost as well as investment cost.**

$$\max_{\substack{X_{g,\tau,t} \\ ICAP_{g,t} \\ CAP_{g,t} \\ E_{g,t}}} \sum_t \beta^t \left\{ \int_0^{D_t(P_t)} P_t(D_t)dD_t - \sum_{(f,g)\in M,\tau\leq t} \left[X_{g,\tau,t} \frac{pf_f}{\eta_{g,\tau}} + c_g \right] - \sum_g PI_{g,t} * ICAP_{g,t} \right\}$$

- **Modeled as non-linear program in GAMS and solved using the CONOPT solver**

Scenarios

	Scenario Description
Base Case	No learning rates, CO_2 emissions are limited
Scenario 1: Emission Reduction	Permit allocation is reduced by 1% each period to increase attractiveness of the low-carbon technology CCS.
Scenario 2: Phase out of nuclear	No investment into nuclear power plant capacity allowed
Scenario 3: Learning effects	Learning effects which lower capital costs and increase efficiency are implemented for the CCS technology and wind, nuclear still allowed for
	Learning effects which lower capital costs and increase efficiency are implemented for the CCS technology and wind, nuclear not allowed for

Data

		Nuclear	NGCC	Lignite	Lignite CCS	Wind onshore	Wind offshore
Full load hours	[h/yr]	7500	7000	7000	7000	1750	3500
Initial Efficiency	[%]	35	58	44	32	0	0
Initial capital costs	€/kW	2500	750	1200	2100	1500	3000
Life time	Years	40	30	40	40	20	20
O&M costs	[€/MWh]	3	2	3	6 + 7 (TS)	2	2

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Learning and Fuel Parameters

Technology	Elasticity eta	$gen_{g;0}$ [TWh]	Elasticity CC	$cap_{g;0}$ [GW]
CCS	-0.025	10	0.1	4
Wind onshore	-	-	0.18	20
Wind offshore	-	-	0.18	4

Fuel		**Uranium**	**Natural Gas**	**Lignite**
Price	**[€/MWh_{th}]**	**5**	**20**	**5**
Carbon emission factor	**[CO2/MWhth]**	**0**	**0,2**	**0,4**
Price	**%**	**1**	**2**	**1**

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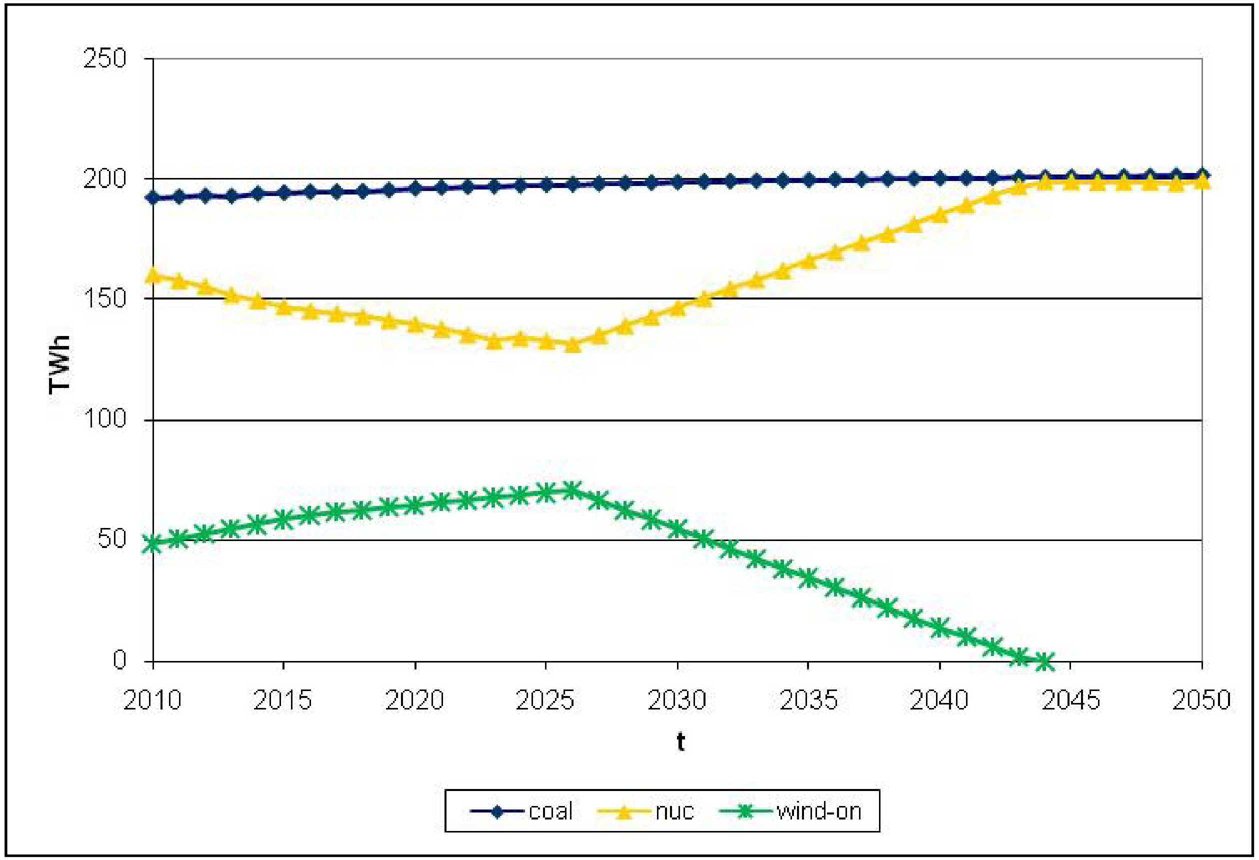
Model Results Base Case

- Lignite electricity production up to the emission constraint
- No endogenous investment in wind capacity
- Nuclear the most competitive alternative to lignite



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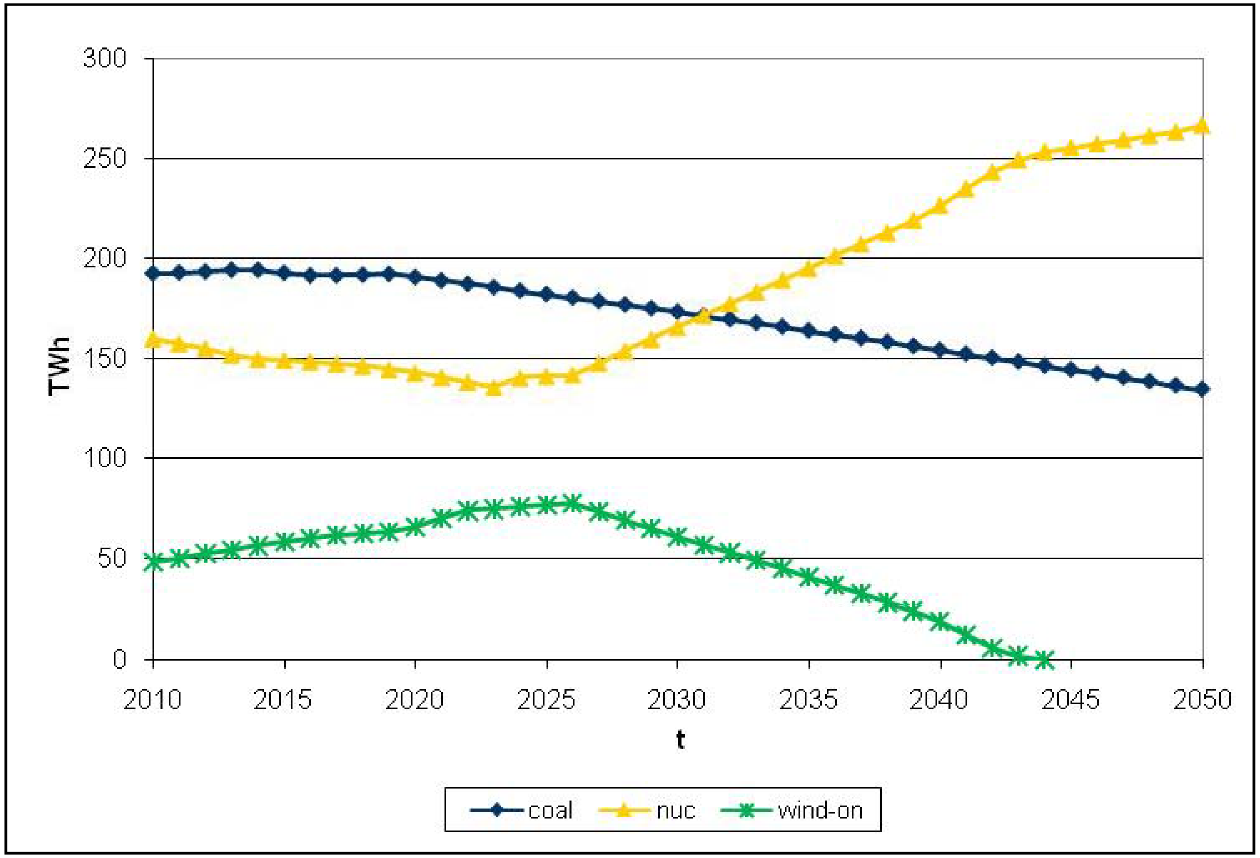
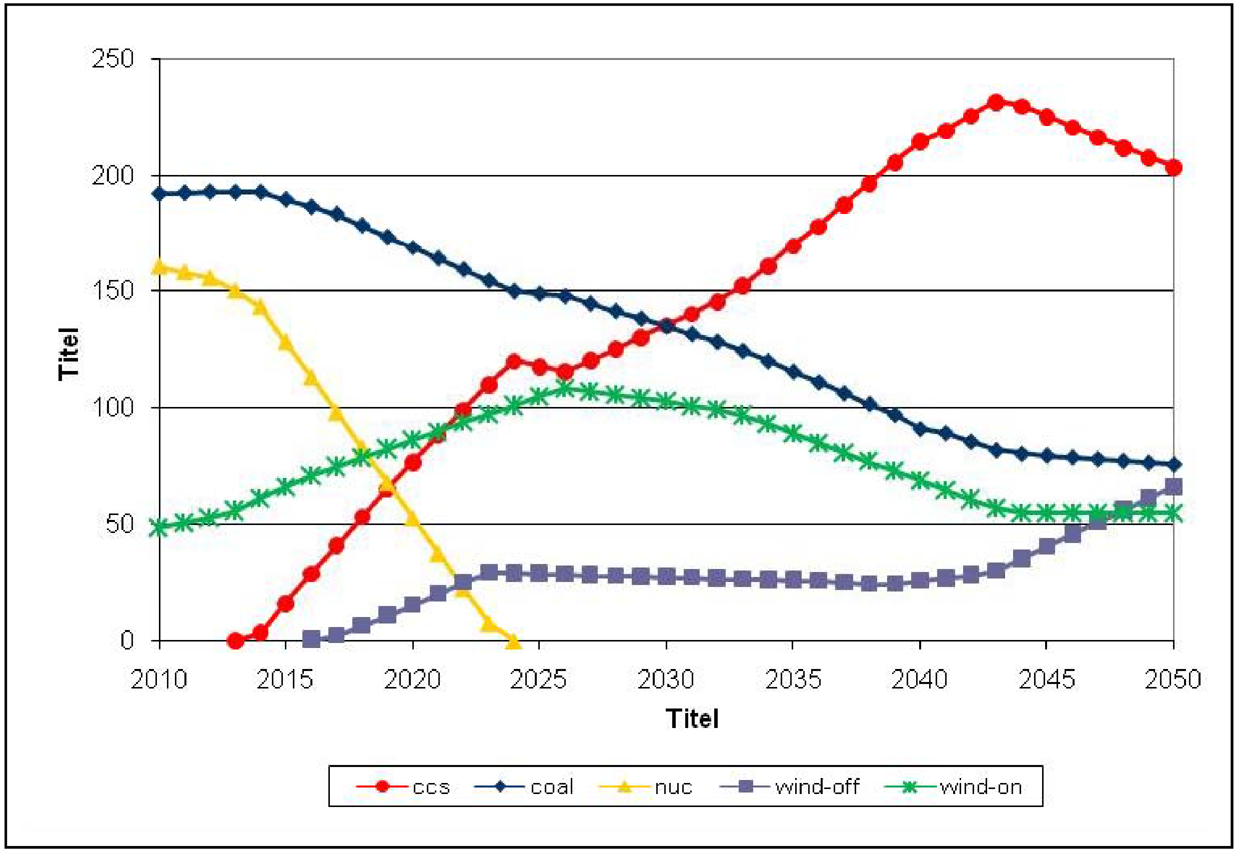
Scenario 1: Emission Reduction

- **Lignite electricity production up to the emission constraint**
- **No endogenous investment in wind capacity**
- **Nuclear fills the opening gap from reduced lignite capacity**



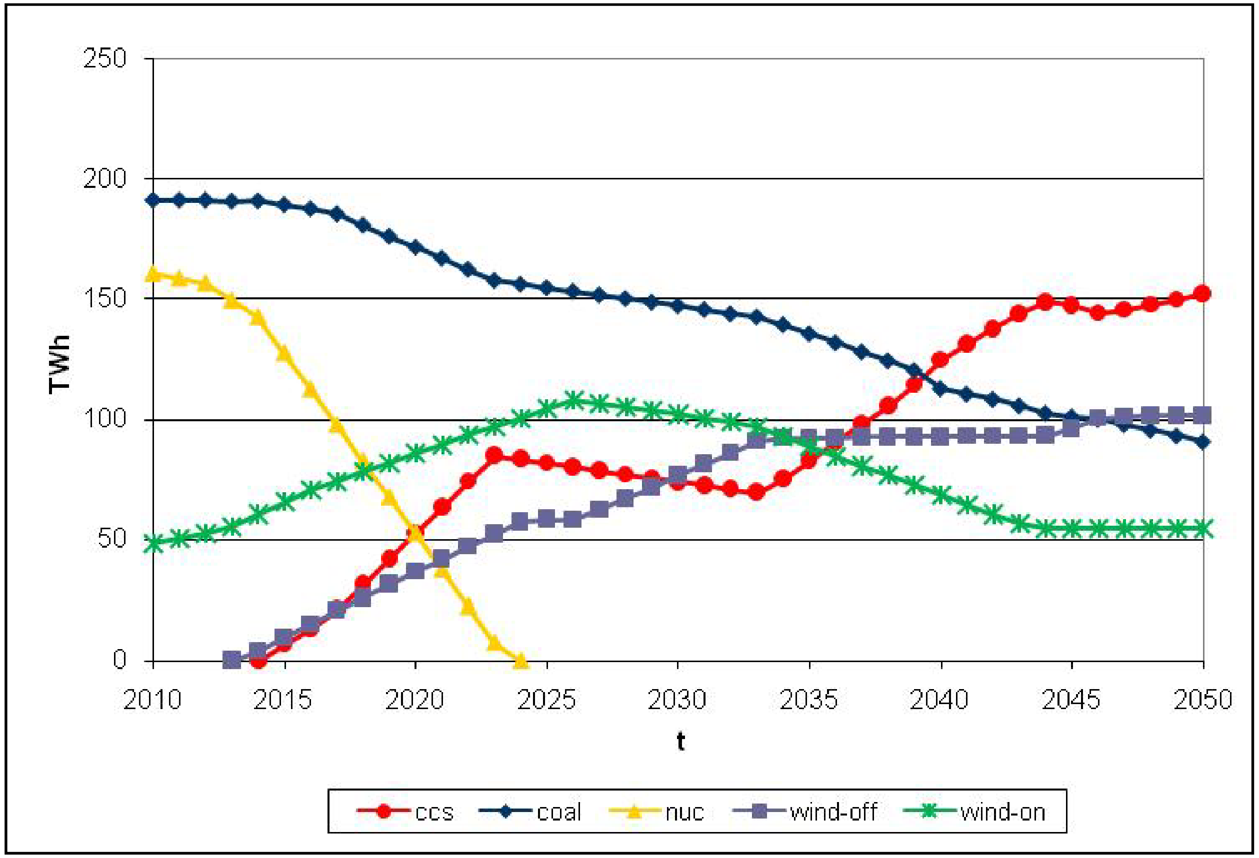
Scenario 2: Emission Reduction, no Nuclear

- **Major investment in CCS technology**
- **Endogenous investment in wind, for offshore the capacity limit not reached**
- **Highest electricity price scenario 83€/MWh in average**



Scenario 3: Emission Reduction, Nuclear Phase-out, Learning

- **Investment into offshore wind from 1012 until capacity restriction is reached**
- **More diverse generation portfolio, CCS acts as a bridge technology**
- **Average electricity price of 68€/MWh**



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Conclusion

- **Low carbon alternatives do not enter the market unless very stringent polices (the phase out of nuclear energy production and a significant reduction in emission allowances) are implemented.**
- **The impact of learning on electricity prices is significant.**

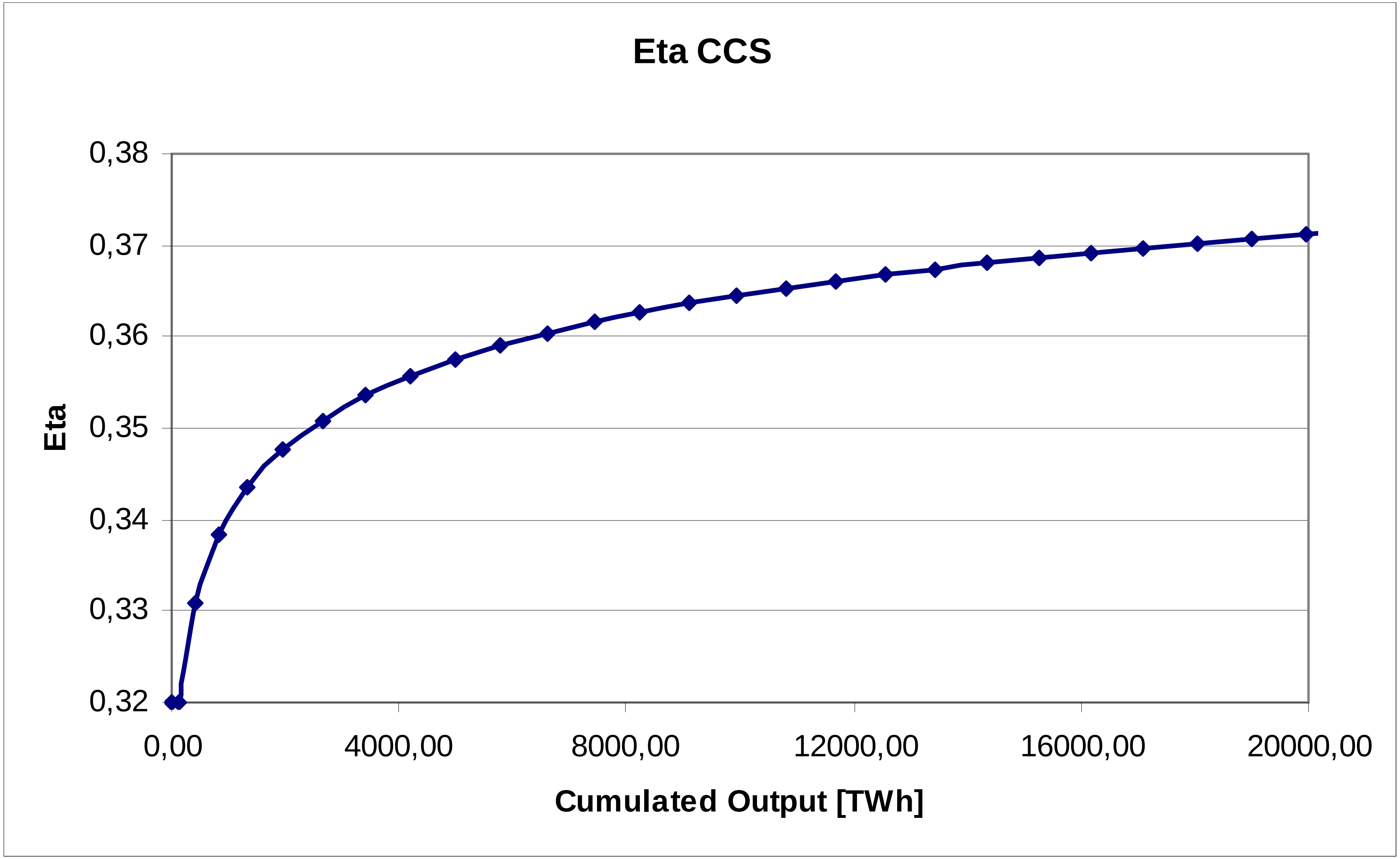
Scenario	BAU	S1	S2	S3
Electricity Price	59	61	83	68
Shadow price CO_2	5	5.5	8	5

- **For offshore wind, learning is even more crucial for its application**
- **CCS is no thread to the deployment of cost competitive or potentially cost competitive renewable technologies**
- **Natural gas plays no role in the CCS base-load scenario with or without learning effects.**

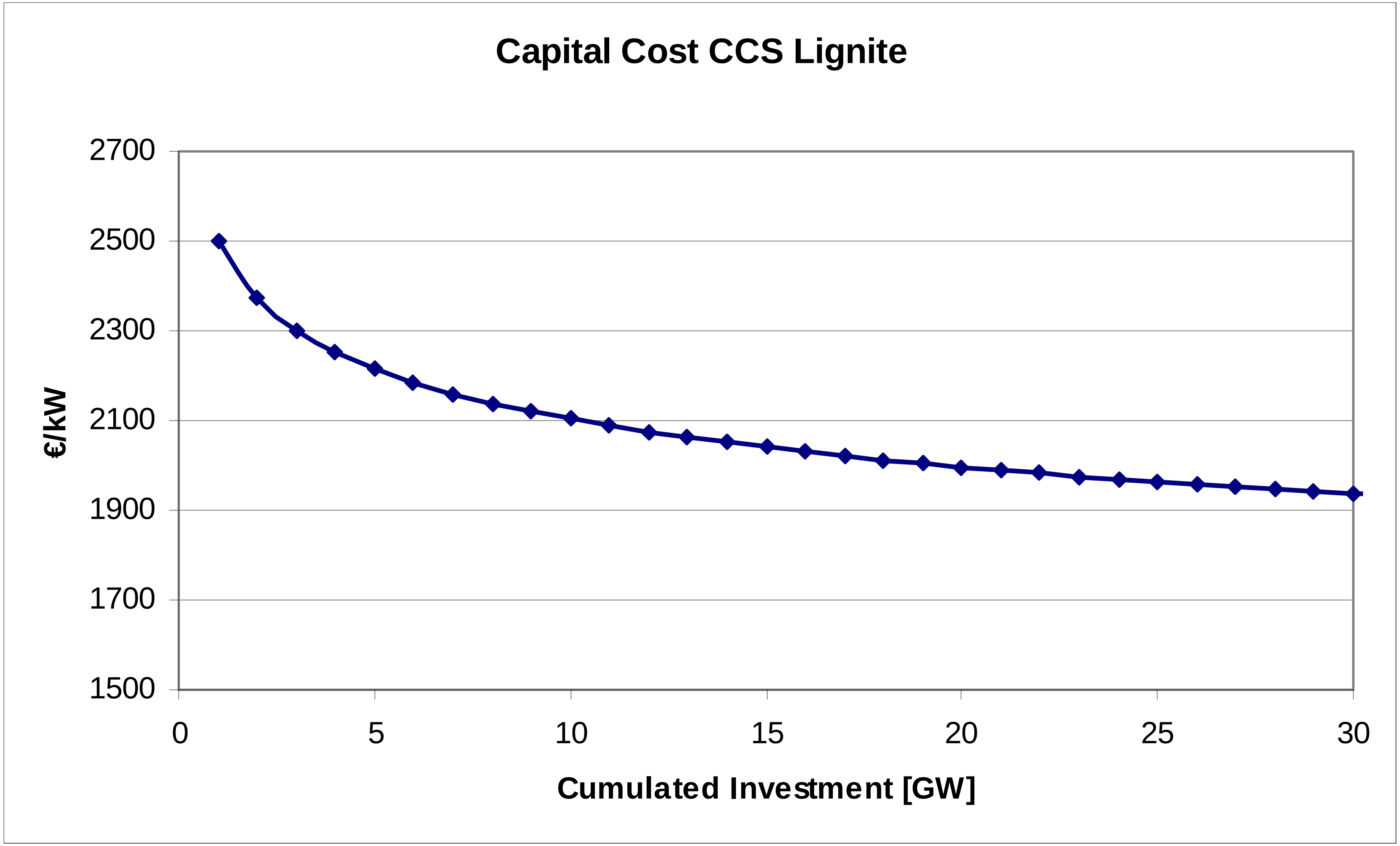
Thank you for your Attention

Questions and Comments are welcome

Scenario 3: Learning Effect Efficiency



Scenario 3: Learning Effect Capital Costs



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