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Assessment of Clean-Coal Strategies: The Questionable Merits of Carbon Capture-Readiness

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Abstract

In this paper we investigate the value of capture-readiness by modeling the cost effectiveness of various alternative technological options and focusing on different clean-coal technology pathways. The modeling framework developed is based on stochastic net present value calculations. It allows for consideration of path-dependent and technology-specific risk combinations inherent in the input and output commodities that are relevant for operating the plant. We find that capture-readiness competes with alternative options of power plant replacements and that capture-readiness is not necessarily preferable from an economic perspective.

Key words: CCS; Capture-ready; Coal combustion; Retrofit

1 Introduction

Carbon capture and storage (CCS) is seen by many international organizations (IEA, 2010; World Energy Council, 2007), the European Commission (European Commission, 2011), and on national levels (Nitsch et al., 2010) to play a major role in reducing carbon dioxide emissions. In recent years, many performance and cost studies of new coal- and gas-fired power plants have been conducted (Bohm et al., 2007; Cormos, 2012; Davison, 2007; Lucquiaud et al., 2011; Rubin et al., 2007). However, the technology is either not yet commercially available or not economically reasonable for the large-scale coal-fired power plants that are built today. At the same time, many new plants of this kind are being built, and they will emit large amounts of carbon dioxide in the future. China, for instance, is expected to increase the capacity of its coal-fired power plants by 485 GW from 2008 to 2035 (EIA, 2011), which is an increase of about 150 percent compared to the estimated 557 GW of operating coal-fired capacity. Therefore, capture-ready power plants seem to be an attractive solution, enabling a later retrofit. This capture-readiness may include different investments, such as extra space for large utilities, a modified turbine with a throttling valve at the intermediate pressure/ low pressure crossover pipe of the steam turbine section, additional foundations, cable trays, and pipe racks. The costs for those modifications are found to be less than five percent of the total investment cost of a coal-fired power plant (Grol, 2012).

The economic value of such capture-ready investments has to be investigated cautiously, because a modest increase in the investment cost translates directly into a few hundred million Euro. The major parameter influencing the value of capture-readiness is the time of CCS-retrofitting and the discount rate applied to the future cash flows. In order to determine the optimal time of retrofitting, it is important to account for alternative technical options available for switching from conventional coal-fired power plants to coal-fired CCS power plants. Such options compete with the retrofit of a capture-ready power plant and might be preferred, further delaying the necessity of retrofits of CCS-ready power plants and reducing the option value of capture-readiness. The lock-in of four specific retrofits

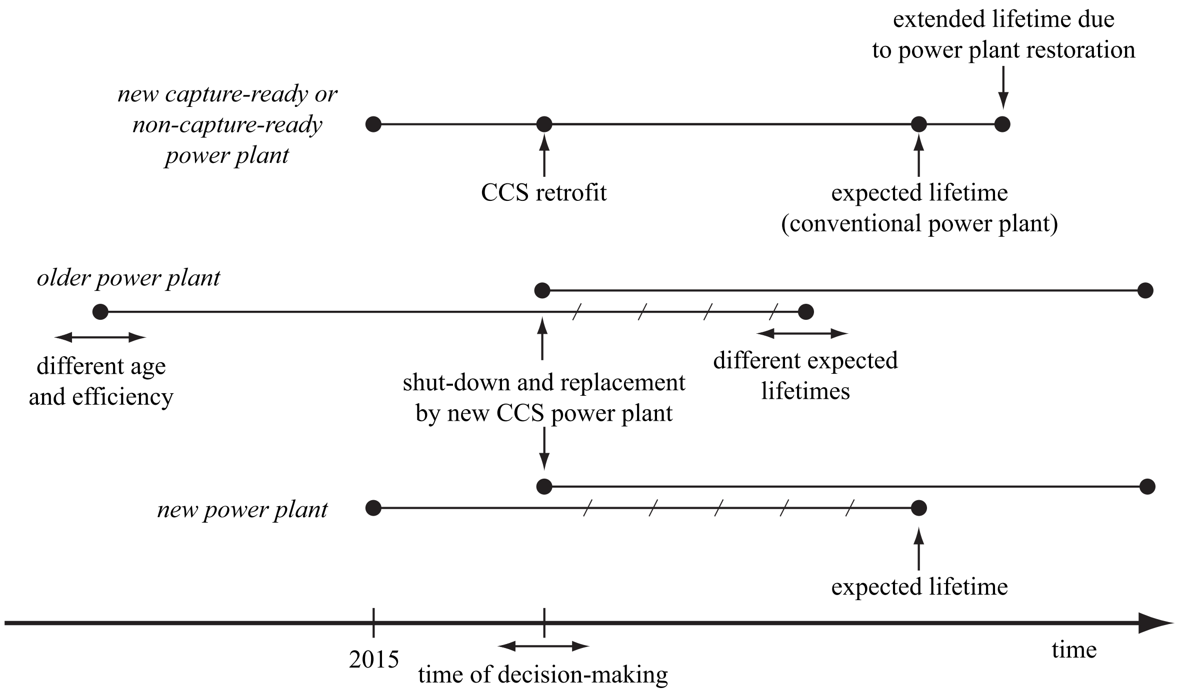

Figure 1: Pathways from conventional coal-fired power plants to a clean-coal technology.

(non capture-ready and three different technical capture-ready configurations) were investigated in a recent study (Liang et al., 2009). The authors found a non-significant impact of capture-ready pre-investments on the probability of a later retrofit (estimated to be around 50 percent). Another study investigates the economic value of retrofitting four Portuguese fossil fuel power plants with CCS (Gerbelov et al., 2013). Interestingly, they found a 50 percent higher break-even price of CO_2 (where the cost of electricity is equal for plants with and without CCS) for a power plant whose remaining lifetime is 30 years, compared to an old power plant whose remaining lifetime is only 17 years. This – at first sight – surprising result is caused by the very low efficiency of the old power plant that results in high specific carbon dioxide emissions. However, the authors do not account for an early closure of the power plant. Although the first-mentioned authors did account for an early closure of the power plant, neither study accounts for the option of replacing existing plants by new CCS power plants.

For our analysis, we use an advanced net present value (NPV) modeling approach. In particular, we are interested in the optimal investment timing for the investment in alternative coal-fired power plants, given specific situations regarding the age of existing power plants and whether or not they were built as CCS-ready. Options considered in this study for investments after 2020 are (cf. Fig. 1): First, retrofitting a modern ($\eta = 47\%$) coal-fired power plant (capture-ready or non-capture-ready). Second, the replacement of older power plants with an efficiency of between 35 and 40 percent (including an early shut-down) and the construction of a new CCS power plant. Third, the early shut-down of a modern power plant ($\eta = 47\%$) and construction of a new CCS power plant. Although the third option seems at first sight pathetic, multiple serious justifications for this option do exist. The penalty in terms of a net efficiency loss of a new CCS power plant is, in general, less than the penalty in net efficiency of a retrofit. The attractiveness of a CCS retrofit decreases with the lifetime of the plant. Generally, just like with energy retrofits of buildings, the retrofit of the entire coal-fired power plant can sometimes be expected to be more expensive than a demolition and subsequent new build.

The fact that multiple alternatives to a capture-retrofit are preferred will delay the need for retrofits, further reducing its probability. In this study we do not consider more cost-effective alternatives to reduce CO_2 emissions, such as nuclear power plants for low-emissions base-load electricity (Nicholson et al., 2011) or renewable energies, which also compete with electricity generation from fossil fuels (Rohlfs and Madlener, 2011a). The renewable technologies with fluctuating supply reduce the full-load hours of base-load power plants and render them less attractive (Lund and Mathiesen, 2012).

The economic modeling is challenging, because of path- and technology-dependent risk stemming from the high price uncertainty of the underlying assets (e.g. electricity price, CO_2 permit price) as well as the correlation of those assets with each other. By describing the various investment options as combinations of those assets, the resulting investment risk becomes endogenous and technology-dependent.

The original contribution of this paper is twofold: On the one hand, we develop a new modeling framework that enables a comparison of different investment options by using endogenous, technology-specific, and risk-adjusted dynamic discount rates. On the other hand, the application of this modeling framework enables the determining of a merit order for the investment in clean-coal technologies in terms of (cumulative) probabilities of adoption.

In the analysis we show that the value of capture-readiness is highly questionable due to the competing investment options. We also demonstrate that in many situations it is preferable to shut down a modern coal-fired power plant ($\eta = 47\%$) and construct a new CCS power plant rather than to retrofit a CCS-ready power plant.

The remainder of this paper is structured as follows. Section 2 provides an overview of technical specifications and design requirements for capture-readiness, and reviews the existing literature on this topic. Section 3 introduces the modeling framework, while section 4 reports on the underlying data and assumptions used. Section 5 presents the results and section 6 concludes.

2 Aspects of capture-readiness

Capture-readiness is a term increasingly used, but often without clarity of meaning (EPPSA, 2006; Markusson and Haszeldine, 2010). Studies and statements by various groups and organizations, such as the International Energy Agency Greenhouse Gas R&D Programme (IEA-GHG, 2007), the Global CCS Institute (Global CCS Institute, 2010), and the European Power Plants Suppliers Association (EPPSA, 2006), have proposed definitions and technical requirements for capture-readiness. Moreover, the German technical inspection association TÜV has developed criteria with respect to the current state of knowledge and put together the so-called TÜV NORD Climate Change Standard TN-CC 006 (TÜV NORD Group, 2011).

Apart from definitions and legislative issues, the studies comprise technical specifications for new-build power plants that allow for and facilitate a later retrofit. Those specifications will lower the effort and the cost associated with a later retrofit of the power plant, reducing the overall CO_2 mitigation costs. The technical requirements, which aim at a reduction of the plant outage time during the retrofit and a high flexibility (e.g. by allowing to take advantage of technical improvements in CCS), concern among others the following (cf. (Global CCS Institute, 2010; IEA-GHG, 2007)):

- choice of the power plant's location with suitable storage sites,
- space for additional systems and components (e.g. CO_2 separation unit, compression unit, extension of cooling water system, temporal storage of compressed CO_2),
- modifications in the initial design of the steam turbine,
- additional foundations, cable trays, and pipe racks.

All such prior modifications of the power plant must not negatively affect the main power plant's operations e.g. through a reduced net efficiency or higher outage times. Nevertheless, some disadvantages of capture-readiness cannot be ignored:

- As CCS investments involve huge construction costs with the expectation of long lifetimes and high utilization hours (Lund and Mathiesen, 2012), the retrofit of older power plants is not reasonable if the remaining lifetime of the power plant is too short. Large-scale power plants built today will be at least ten to fifteen years old by the time they are retrofitted, as otherwise they would have been built as CCS plants right away. Moreover, the CCS technology is not expected to be commercially available before 2020 (Nitsch et al., 2010). Due to the delayed retrofit, the remaining lifetime of capture-ready power plants is lower than that of a new-build CCS power plant. Finally, after 2020 there will be older power plants that were constructed in the 1990s, 1980s, and 1970s with net efficiencies of around 35%, and whose shut-down and replacement with a new CCS power plant will also compete with a CCS retrofit of a capture-ready power plant.
- The requirements of capture-readiness are based on today's technical knowledge (for instance, the knowledge about embodied post-combustion amine-based scrubbers). To minimize the efficiency penalty, Harkin et al. (2012) request that the design of a solvent-based CCS plant should be conducted with the understanding of how the

power station will interact with the CCS equipment and especially with the specific solvent. Only a smart heat integration can decrease the energy (or more precisely, the exergy) demand for the desorption process. As carbon capture (and power plant) technology will develop further (as for instance, by using other capturing methods, like membrane or cryogenic processes (Mondal et al., 2012; Olajire, 2010)), capture-readiness measures run the risk of becoming obsolete or even counter-productive over time (Markusson and Haszeldine, 2009).

- Capture-ready investments may include additional equipment, such as valves or turbine modifications. This additional equipment also requires maintenance, thus inducing higher maintenance costs, and may negatively impact the availability or the flexibility of the plant.

Overall, it becomes clear that the benefits or disbenefits of capture-readiness have to be carefully balanced against each other. Intuitively, it also becomes obvious that capture-readiness may not be advantageous in all situations.

3 Model specifications

3.1 Basic motivation

The value of capture-readiness is strongly influenced by the delay time between the construction of the coal-fired power plant and the later CCS retrofit. This delay time is affected by other technical options which compete with the retrofit and might allow carbon dioxide emission reductions at lower costs. Therefore, the relative economic merit of the different technological options has to be considered in order to estimate when a CCS-ready power plant ought to be retrofitted.

The value of the different technologies mainly depends on the specific cost of investment and the incoming and outgoing cash flows (revenues and costs). These cash flows can generally be seen as a technology-dependent combination of the price of basic underlying assets, such as the price of electricity, fuel, and carbon dioxide allowances, which may themselves be modeled as correlated stochastic prices.

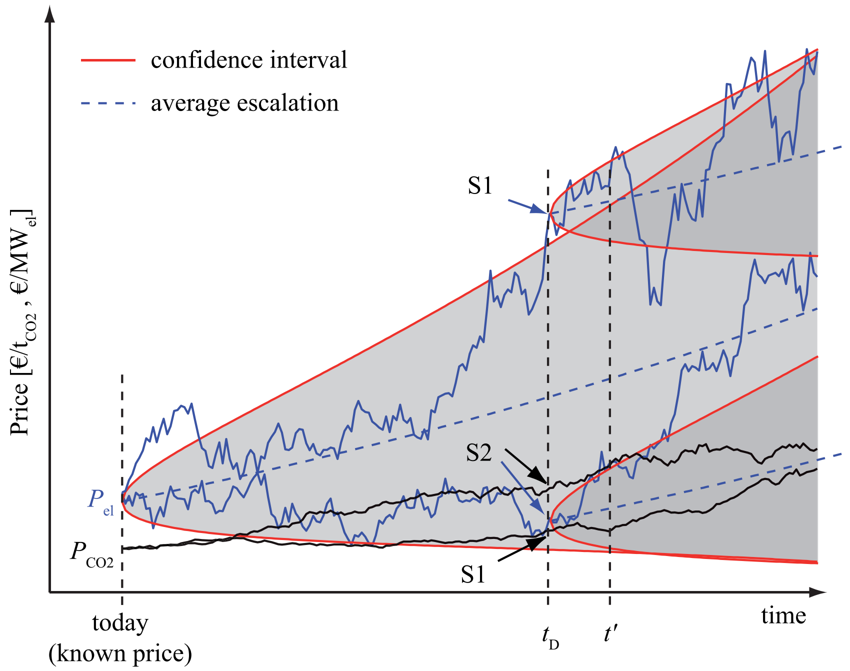

Figure 2: Illustration of two correlated geometric Brownian motion price processes for electricity and coal

Figure 2 depicts exemplarily two of these price paths for each asset (electricity and carbon dioxide). Starting off from the known price of today, an infinite number of possible price paths can be drawn, whose confidence interval (enveloping the majority of price paths) increases with time. Evaluating the investment decision at time t_D, different states of the world have to be considered, taking the uncertainty of the future prices into account. For simplicity, let us focus on two states only: S1 and S2. In S1, the electricity price is much higher than in S2, not only in absolute terms but also relative to the price of carbon dioxide emission permits. This change in the price ratio implies that the investment is much less affected by the carbon dioxide price in S1 than in S2. Therefore, it is obvious that the combination of the different uncertain cash flows as one net cash flow is not only technology-dependent, but also state-dependent, which results in a technology- and a state-dependent risk.

Another important characteristic of the investment is that cash flows are generated continuously during the power plant's operation, which is why net cash flows from different periods have to be adequately discounted and added up. Caused by a strong but imperfect correlation between the prices in time t_{D} and t' from today's point of view (note that it is most unlikely that the price of S1 at t_{D} will jump to the price of S2 in t') a simple addition of cash flows gained in different periods is impossible.

In the following section, we present a model-based approach, which accounts for the above mentioned complications in economically evaluating power plants and clean-coal strategies.

3.2 Model description

For modeling the above described complex decision problem we introduce a novel combination of a multi-dimensional lattice and a Monte-Carlo simulation technique. The four major steps of the model development are described in the following.

First, we construct a multi-dimensional tree of order $n + 1$, where n is the number of underlying assets. All assets are described by correlated geometric Brownian motion processes with constant volatility and drift[1]. The additional asset (referred to as "baseline asset") describes the general market development. This is used to determine the correlation of the "combined asset" with the market in order to be able to later apply the well-known Capital Asset Pricing Model (Lintner, 1965; Sharpe, 1964) (CAPM) from the finance literature for endogenous risk-adjusted discounting.

Second, we determine the expected internal rate of return, its volatility and its correlation to the market at each node, as each node of the decision tree represents a point in time and a state of the world at which the investor has the opportunity to decide whether or not to invest in one of the various technologies available. To do this, we solve the following equation with respect to the internal rate of return, $\mu(j, t^*)$, discretized in time using

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[1] The choice of geometric Brownian motion processes has been made in this study. Note that the general approach of the model is not limited to the choice of this process.

Monte-Carlo simulation.

$$\int_{t^*}^{t^*+T_{LT(j)}} \sum_i c_i(j,t^*) \cdot P_i(t) \cdot e^{\mu(j,t^*)\cdot t} dt - I(t^*,j) = 0, \tag{1}$$

where t^* denotes the variable time of the investment and $T_{LT(j)}$ the expected lifetime of the specific power plant j. The technology-dependent input and output quantities are given by $c_i(j,t^*)$, while $P_i(t)$ is the time-dependent price of the commodity i. The variable $I(t^*,j)$ denotes the time- and technology-dependent investment costs. Each simulated combination of price paths results in a rate of return for each technology and a correlated development of the baseline asset. From these data, the expected rate of return, $E(\mu(j))$, its variance, $Var(\mu(j))$, and its correlation with the market (baseline asset), $Corr(\mu(j),\mu(M))$, are determined.

Third, using the CAPM, an endogenous, technology- and state-dependent required rate of return, δ_j, can be calculated for each technology by using the following relationship

$$\delta_j = r + \Phi \cdot Var(\mu(j)) \cdot Corr(\mu(j),\mu(M)), \tag{2}$$

where r denotes the risk-free rate of return and Φ the market price of risk, defined as

$$\Phi = \frac{E(\mu(M)) - r}{Var(\mu(M))}. \tag{3}$$

Finally, a decision rule is applied, maximizing the difference between the expected and required rate of return of all different technologies, j, considered, i.e.

$$\max(E(\mu(j)) - \delta_j, 0). \tag{4}$$

For the case where this difference is less than zero, the investor should refrain from investing. Note that the use of this profitability-based decision rule also allows a comparison of different sized projects.

4 Data and assumptions

4.1 Technical specifications

In this study, technical data and assumptions for various coal-fired power plants (with and without CCS) have been used. The following section summarizes and explains these data.

4.1.1 Existing power plants

The three existing power plant facilities, which can be either retrofitted or shut down, comprise a modern state-of-the-art hard coal power plant as well as two older power plants built twenty to thirty years ago. Table 1 depicts the assumed net efficiency, η, the regular shutdown time, T_{LT}, the yearly coal consumption, $\dot{m}_{\mathrm{coal}}$, the electricity output, W_{el}, and the carbon dioxide emissions, $\dot{m}_{\mathrm{CO2}}$. All power plants are assumed to have the same net electricity output of 500 $\mathrm{MW_{el}}$ and 5000 full-load hours, which is equal to a capacity factor of 60%. Fuel consumption is calculated based on a heating value of $H_{\mathrm{v}} = 8.5\,{}^{\mathrm{MWh}}/_{\mathrm{t}}$. The carbon dioxide emissions from burning one tonne of hard coal are $2.62\,{}^{\mathrm{t_{CO2}}}/_{\mathrm{t_{coal}}}$.

4.1.2 New carbon capture power plants

In this study, additionally to retrofitting an existing capture-ready power plant (**HC-CCS-CR**), we consider the option of retrofitting a non-capture-ready (**HC-CCS-NCR**) power plant and the construction of a new gasification combined-cycle power plant with CCS (**HC-IGCC-CCS**), which is seen to have high net efficiencies compared to pulverized coal-fired power plants (Hammond et al., 2011). Those IGCC-CCS power plants can be equipped with an amine absorption unit using an aqueous solution of MEA, which is at

Table 1: Specification of the existing power plants

Technology option	η [%]	T_{LT} [a]	$\dot{m}_{\mathrm{coal}}$ [t/a]	$\dot{m}_{\mathrm{CO2}}$ [t/a]	W_{el} [$\mathrm{TWh_{el}}$/a]
New hard coal power plant	47%	2050	$6.3 \cdot 10^5$	$1.64 \cdot 10^6$	2.50
Old hard coal power plant #1	35%	2030	$8.4 \cdot 10^5$	$2.20 \cdot 10^6$	2.50
Old hard coal power plant #2	40%	2040	$7.4 \cdot 10^5$	$1.92 \cdot 10^6$	2.50

present the only technology commercially available, and which could be implemented in large scale. However, better alternatives may be given by polymeric membranes, which can decrease the energy intensity for the separation process by 15 times compared to an amine absorption process (Skorek-Osikowska et al., 2012).

Notwithstanding the plethora of published cost estimates that are available, it must be remembered that neither a full-scale power plant with CCS has yet been built nor a retrofit been conducted (Rubin, 2012). Thus, cost estimates and technical specifications must be seen as assumptions, for which we perform a variety of sensitivity analyses in this study. For the base case, the technical specifications of the new **HC-IGCC-CCS** are taken from the German "Pilot Study 2010" ("Leitstudie 2010" Nitsch et al., 2010), which provides projections for the required specifications until 2050. Those projections include an increase in net efficiency and a reduction of the investment cost in order to reflect future changes in performance and cost, in line with Riahi et al. (2004).

For the retrofit of a capture-ready and a non-capture-ready pulverized coal-fired power plant with a capture rate of 85%, a lower net efficiency has been assumed compared to the new **HC-IGCC-CCS**power plant. Note that the energy penalty between the new power plant built in 2015 and the retrofit in the year 2020 is 8 to 9 percentage points. However, it should be kept in mind that a new IGCC power plant, built in 2020, is assumed to have an efficiency of 52% (Nitsch et al., 2010), resulting in an energy efficiency drop of 7 percentage points, which is in line with recent studies (Cormos, 2012).

The cost of investment for the capture-ready case is taken to be the difference between the cost of an **HC-IGCC-CCS** power plant and an **HC-IGCC** power plant according to (Nitsch et al., 2010). For the non-capture-ready case, an additional decrease in net efficiency of one percentage point as well as a fifty percent increase in the specific cost of investment is presumed. The lifetime of the retrofitted power plant is 125 percent of the remaining lifetime of a plant built in 2015. Table 2 summarizes the time-dependent specifications of the CCS power plants.

The specifications assumed for an investment in CCS in the year 2030 are given in Table 3. Note that, due to the fixed boiler size in the case of a retrofit, the net electricity

Table 2: Time-dependent specification of the CCS power plants

Technology option	Parameter	Unit	Year 2020	 2030	 2040	 2050
Retrofit of a capture-ready power plant with CCS, **HC-CCS-CR**	Net efficiency	[%]	39	41	41	41
	Investment cost	[€/kW$_{\text{p}}$]	700	700	700	700
	CO_2 emissions	[kg/MWh$_{\text{el}}$]	119	113	113	113
Retrofit of a non-capture-ready power plant with CCS, **HC-CCS-NCR**	Net efficiency	[h/a]	38	40	40	40
	Investment cost	[€/kW$_{\text{p}}$]	1150	1150	1150	1150
	CO_2 emissions	[kg/MWh$_{\text{el}}$]	122	116	116	116
New gasification combined cycle plant with CCS, **HC-IGCC-CCS** Nitsch et al. (2010)	Net efficiency	[h/a]	43	45	45	45
	Investment cost	[€/kW$_{\text{p}}$]	2200	2200	2200	2200
	CO_2 emissions	[kg/MWh$_{\text{el}}$]	107	102	102	102

Note: The annual O&M costs are equal to 2% of the investment cost, the assumed plant lifetime is 25 years.

output is reduced, while the coal consumption remains constant. For a new CCS power plant, the electric output remains at 500 MW$_{\text{el}}$, leading to higher fuel consumption and higher carbon dioxide emissions. The amount of carbon dioxide required to be transported and stored is 5.66 times higher due to a capture rate of 85%.

In this study, we examine the value of capture-readiness by identifying the point in time when it is economically reasonable to switch from conventional coal-fired to CCS power plants. This implies that the revenues and costs associated with the retrofit (or the replacement of an older power station by a new CCS plant) are given by the difference between the cash flows gained from the conventional plant and from the CCS power plant. In Table 4, this is again shown for an investment in 2030. For retrofitting, this causes lower carbon dioxide emissions at the cost of a lower electricity output and additional expenditures for transportation and storage (T&S costs). For a premature shut-down of an old power station, the difference in the cash flows can be divided into two time intervals. In the first interval, which lasts from the premature shut-down to the planned shut-down, the net electricity output remains constant, while fuel consumption increases and carbon dioxide emissions decrease. From the planned shut-down to the end of the new power plant's lifetime, the inputs and outputs correspond to those of the new power plant. Note

Table 3: Specification of the CCS power plants for an investment in 2030

Technology option	η [%]	ΔT_{LT} [a]	C_{Inv} [M€]	$\dot{m}_{\mathrm{coal}}$ [t/a]	$\dot{m}_{\mathrm{CO2}}$ [t/a]	W_{el} [TWh$_{\mathrm{el}}$/a]
Retrofit new **HC-CCS-CR**	41%	12.5	320	$6.3 \cdot 10^5$	$1.6 \cdot 10^5$	2.18
Retrofit new **HC-CCS-NCR**	40%	12.5	514	$6.3 \cdot 10^5$	$1.6 \cdot 10^5$	2.13
New **HC-IGCC-CCS**	45%	25.0	1125	$6.6 \cdot 10^5$	$1.7 \cdot 10^5$	2.50

Table 4: Difference in input and output quantities for an investment in 2030

Strategy	Time span	$\dot{m}_{\mathrm{coal}}$ [t/a]	$\dot{m}_{\mathrm{CO2}}$ [t/a]	W_{el} [TWh$_{\mathrm{el}}$/a]
Retrofit new **HC-CCS-CR**	2030 – 2050	0	$-1.4 \cdot 10^6$	−0.32
	2050 – 2052	$6.3 \cdot 10^5$	$2.5 \cdot 10^5$	2.18
Retrofit new **HC-CCS-NCR**	2030 – 2050	0	$-1.4 \cdot 10^6$	−0.37
	2050 – 2052	$6.3 \cdot 10^5$	$2.5 \cdot 10^5$	2.13
Shutdown old hard coal #1, new build **HC-IGCC-CCS**	2030 – 2070	$6.5 \cdot 10^5$	$2.6 \cdot 10^5$	2.50
Shutdown old hard coal #2, new build **HC-IGCC-CCS**	2030 – 2040	$-8.2 \cdot 10^4$	$-1.6 \cdot 10^6$	0
	2040 – 2070	$6.5 \cdot 10^5$	$2.6 \cdot 10^5$	2.50
Shutdown new hard coal, new build **HC-IGCC-CCS**	2030 – 2050	$3.0 \cdot 10^4$	$-1.5 \cdot 10^6$	0
	2050 – 2070	$6.6 \cdot 10^5$	$1.7 \cdot 10^5$	2.50

that the revenues gained from replacing a conventional power plant by a CCS power plant only result from the cost savings due to the lower carbon dioxide emissions. Those revenues have to cover the cost of investment as well as the opportunity cost of the lower electricity output (or the higher fuel consumption).

The T&S costs of CO_2 (additionally occurring for the CCS technologies with an absorption rate of 90%) are assumed to be 5 €/t$_{\mathrm{CO2}}$, which is in line with McCoy (2008) and Parsons Brinckerhoff (2011), and is also in line with the "Criteria for Technical and Economic Assessment of Plants with Low CO_2 Emissions" (IEA-GHG, 2009). Additionally, a sensitivity analysis with respect to higher and lower CO_2 T&S costs is conducted.

4.2 Underlying economic data and assumptions

The economic and market boundary conditions are very important, but at the same time also highly controversial. Due to the power plant's long lifetime, long-run price projections for the underlying assets are needed. As the latest investment decision considered is assumed to take place in 2050 (with the technological data provided in section 4.1) and a maximal lifetime of 25 years, price projections until 2075 are required.

Table 5 shows that the parameter set used in our analysis comes from two different sources. On the one hand, to determine the correlation coefficients between the assets, we use historical price data provided by the European Energy Exchange (EEX) for electricity, coal, natural gas, and EU ETS emission allowances. On the other hand, the German stock market index DAX is used for representing the benchmark asset.

In order to estimate the other two important parameters, i.e. the growth rate α_i and the volatility σ_i, in a first go we applied the maximum likelihood method (Hogg and Craig, 1978; Hull, 2005) to the data just mentioned. Expectedly, the parameters estimated from the historical data of the last eight to ten years lead to implausible results if applied over a projection period of 70 years. This is mainly due to the large difference in growth rates and also the high volatilities. Hence, we calculated the missing quantities from the data provided in the German "Pilot Study 2010" (Nitsch et al., 2010), in which three different scenarios (high, moderate, low) with price projections for electricity, coal, gas, and emission

Table 5: Parametrization of the price processes

Parameter	$P_{i,0}$ [€]	α_i	σ_i	$\rho_{i,\text{el}}$	$\rho_{i,\text{coal}}$	$\rho_{i,\text{gas}}$	ρ_{i,CO_2}	$\rho_{i,\text{M}}$
P_{el}^{a}	60	4.00%	4.00%	1.000	0.608	0.702	0.518	0.140
P_{coal}^{b}	69	4.18%	7.09%	0.608	1.000	0.603	0.250	0.260
P_{gas}^{c}	5.5	4.03%	6.70%	0.702	0.603	1.000	0.273	0.150
$P_{\text{CO}_2}^{d}$	20	4.14%	7.07%	0.518	0.250	0.273	1.000	0.201
P_{M}^{e}	1	2.00%	2.00%	0.140	0.260	0.150	0.201	1.000

Notes: [a]base-load futures traded at the EEX (F1BY, July 1, 2002 - February 2, 2012); [b]coal futures traded at the EEX (FT4Y, May 2, 2006 - January 5, 2012); [c]natural gas futures traded at the EEX (G0BY, July 2, 2007 - January 5, 2012); [d]EUA price (F2PE & F2EA, October 4, 2005 - January 5, 2012) at the EEX. [e]German stock market index (DAX, March 2, 1992 - January 5, 2012).

allowances have been proposed. For the growth rates, we used the price developments of the moderate scenario. Note that the prices given in the Pilot Study are in real terms, based on the year 2007. In our model, nominal prices are employed, discounted by a benchmark asset. Because of that, the growth rates applied need to be increased by the growth rate of the benchmark asset ($\alpha_{\mathrm{M}} = 2\%$). For the volatility of the price paths considered in our study, we assume that the variance of the stochastic processes equals the high and low price trajectory assumed in Nitsch et al. (2010) for $t = 2050$. The values estimated are very low, compared to previous studies (Rohlfs and Madlener, 2010, 2011b). Therefore, the proposed model aims at investigating long-run price uncertainties rather than short-run fluctuations. In our opinion, this assumption is justifiable, due to the long construction lead times of the power plants rendering short-run price variations rather unimportant for "strategic" investment decisions.

5 Results

The dynamic net present value analysis with endogenous risk treatment gives insights into the merit order of different clean-coal strategies, which subsequently sheds light on the value of capture-readiness. For the reference case using the data given in Tables 2 to 5, the continuous investment decision is discretized in ten steps ranging from 2015 to 2050. The separate investigation of the various investment options in new coal-fired CCS power plants or capture retrofits leads for each option to a cumulative probability of technology adoption, as shown in Fig. 3.

Due to the non-availability of CCS before 2020, no investment is suggested by the model in the first steps. As soon as CCS becomes available, an almost immediate investment in a new CCS power plant is proposed, replacing the older power plant with an efficiency of 35%, which was originally intended to operate until 2030. The probability of replacing the second existing power plant (efficiency 40% and expected lifetime up to 2040) is slightly higher than 80% in 2025. However, it also increases to almost 100% by the year 2030. For the new power plant (built in 2015 with an efficiency of 47%), the concurring options of a replacement

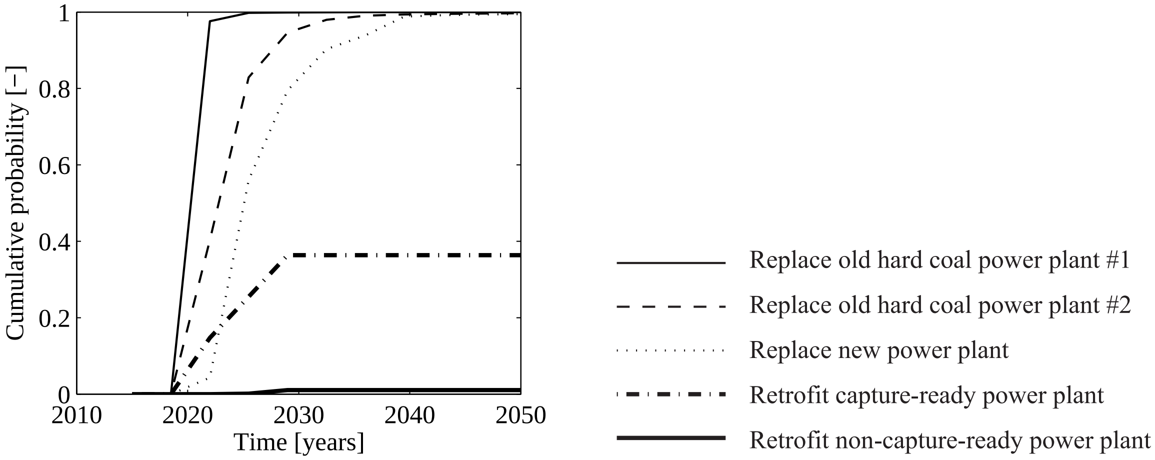


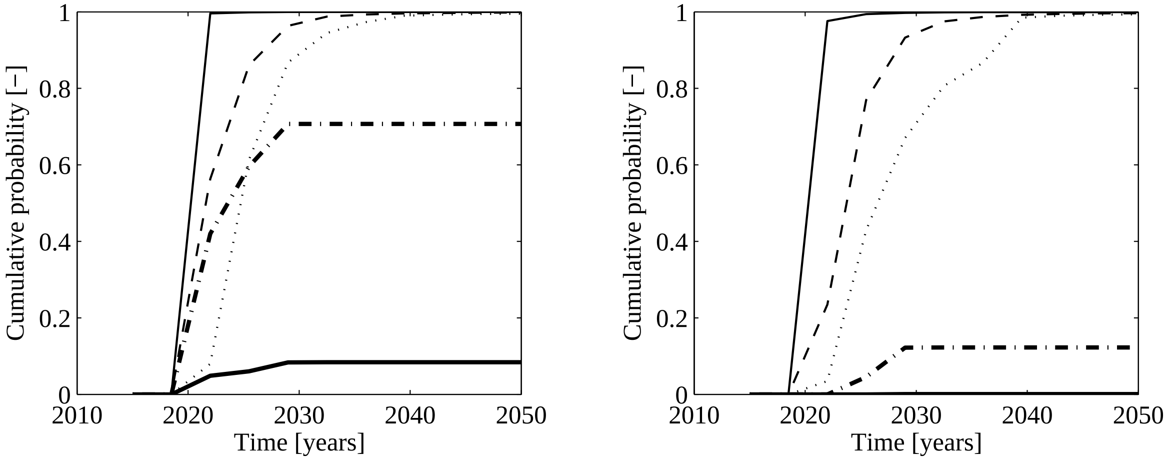
Figure 3: Cumulative probability of the different clean-coal technology pathways, indicating their merit order for the reference case

with a new CCS power plant or the retrofit (capture-ready and non-capture-ready) with CCS are shown by the dotted, chain-dotted and solid lines, respectively. Contrary to prior expectations, the probability of a replacement is much higher than that for a retrofit. However, a large difference between the capture-ready and the non-capture-ready power plant is found. As the retrofit becomes unattractive with increasing age (and decreasing remaining lifetime) of the power plant, the cumulative probability rises only up to 2030. Nevertheless, for the capture-ready case, the cumulative probability stays below 40%.

In the following subsections, we will investigate the influence of different parameters such as the power plants' efficiencies and expected remaining lifetimes, the price levels of the underlying assets, and the cost of investment.

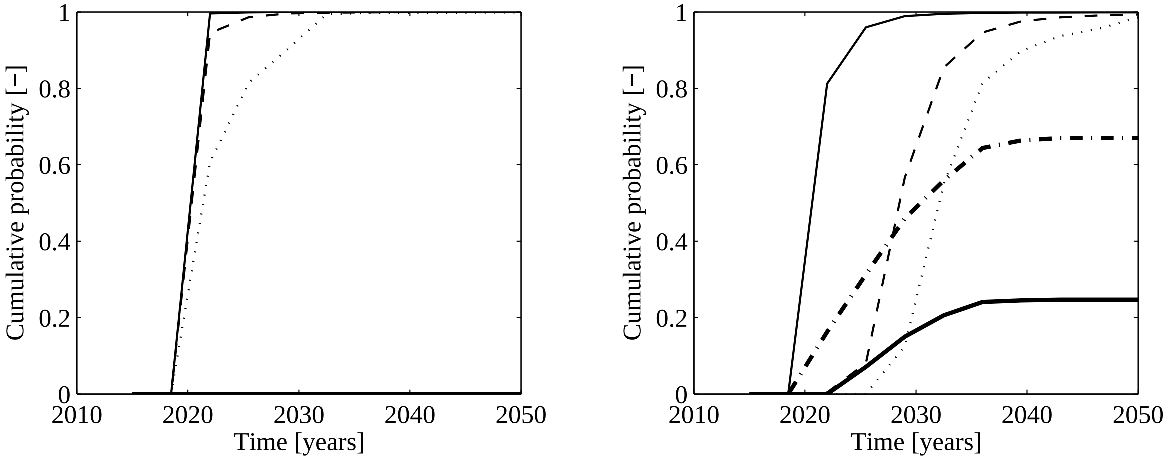
5.1 Influence of efficiencies and expected lifetimes

The technical specifications of the existing power plants, such as the expected remaining lifetime and the efficiency, have a major impact on the investment decision in CCS. For the older power plant, the net efficiency is below that of the new IGCC-CCS power plant. Therefore, the replacement leads to a higher net efficiency and to strongly reduced carbon dioxide emissions. Increasing the older power plant's efficiency lowers the benefit which arises due to the lower fuel intake (assuming an equal electricity output of 500 $\mathrm{MW_{el}}$). Still, the difference between the cumulative probability shown in Figs. 4(a) and 4(b) (depicting a difference in net efficiency of 4 percentage points) is low, caused by the limited remaining lifetime of the older power plant.



(a) Reduction in the efficiency of the existing power plants by 2 percent

(b) Increase in the efficiency of the existing power plants by 2 percent



(c) Reduction in the remaining lifetime of the existing power plants by 10 years

(d) Increase in the remaining lifetime of the existing power plants by 10 years

Figure 4: Influence of the existing power plants' efficiency and expected lifetime on the merit order of the clean-coal technology pathways.

For the new power plant, the variation of the initial efficiency depicts a high influence on the chance of retrofitting. While for a base plant efficiency of 45% a retrofit is very likely, there is hardly any no chance of retrofitting if the base plant's efficiency is 49%.

As we did not vary the efficiency of the retrofitted power plant, these plots compare also the influence of different efficiency penalties caused by the retrofit. For the decreased base-plant efficiency, the penalty is only 4 percentage points, while for the other case, an efficiency penalty of 8 percentage points results. Although it is questionable as to what extent the same efficiency of the retrofitted power plant can be reached for different efficiencies of the base plant, the variation of the base plant's efficiency shows that replacing the base plant by a new CCS power plant is, in the majority of cases, the preferred alternative.

The influence of the expected remaining lifetime is shown in Figs. 4(c) and 4(d). In the case of a reduced lifetime, a nearly direct replacement by CCS power plants is proposed in order to replace the older and the new power plants. Note that in this case, the expected lifetime of the new power plant is only fifteen years. However, more interesting is the second case, where an increased lifetime is investigated. For this case, the probability of retrofitting a capture-ready power plant increases to a value of 60% even before a replacement becomes attractive. The probability of a non-capture-ready power plant reaches a value of above 20% percent. As expected, the probability of a retrofit is very sensitive to the expected lifetime of the power plants.

Comparing the actual age and lifetime of the power plants (which may be as much as forty years or more) with the lifetime expected in economic studies (mostly between 25 and 30 years), it becomes clear that a large discrepancy exists. However, from an economic point of view, the fact that cash flows gained in this period (from 25 to 35 years) are neglected may be reasonable. In the case of a fixed discount rate of 8%, these cash flows account for less than 10% of the overall cash flows. Additionally, lifetime extensions are mostly associated with larger investments for general overhauls, which are not accounted for in the initial investment decision process. However, this analysis shows that for the decision process of CCS-retrofitting, or switching to a new CCS power plant, these extended lifetimes do have a major influence.

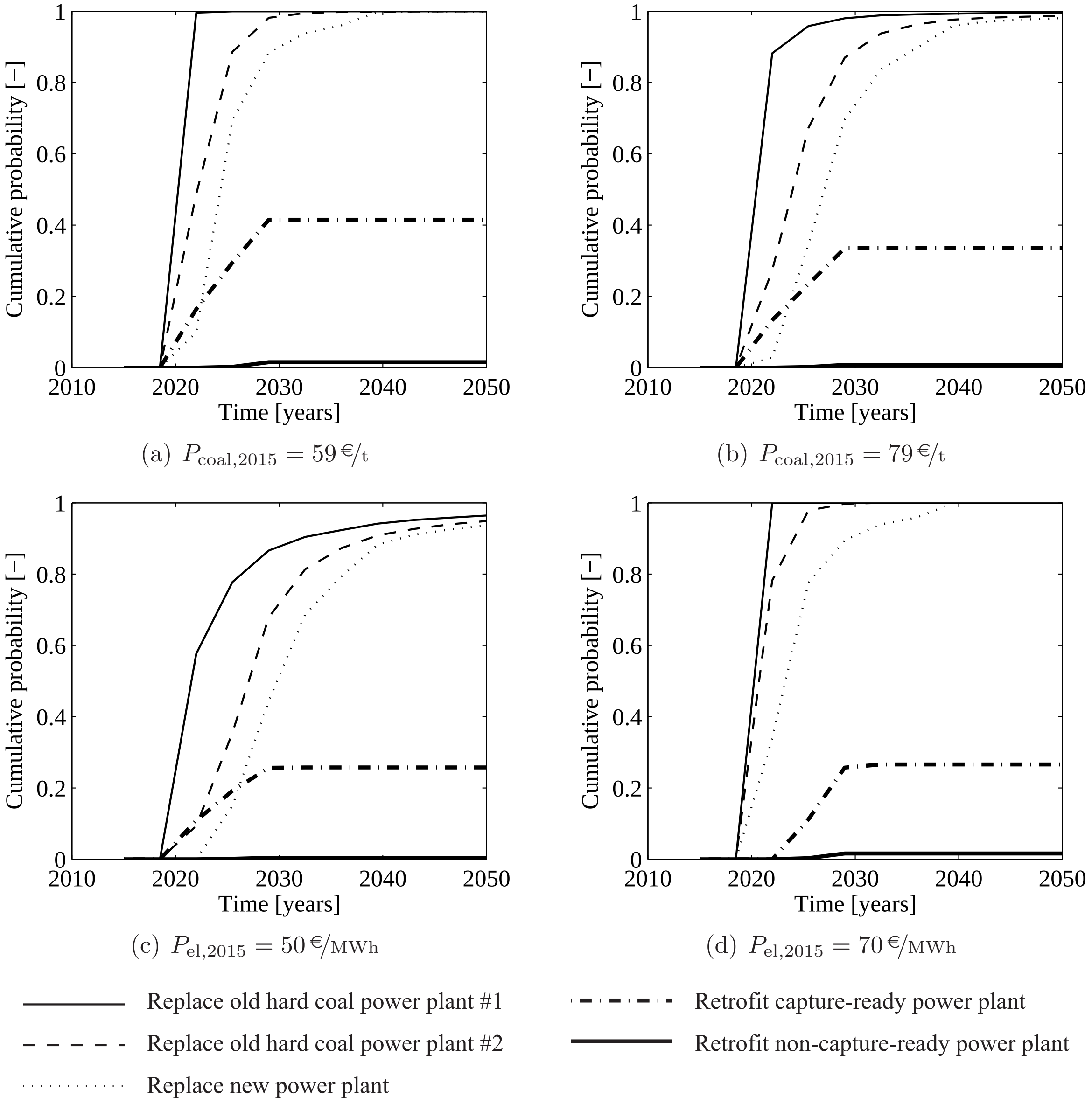
5.2 Influence of price levels

In this subsection, we examine the influence of the prices of the three underlying assets, i.e. the price of electricity, coal, and carbon dioxide certificates as well as the T&S costs.

Figures 5(a) and 5(b) show the influence of the coal price level in 2015. For replacing or retrofitting existing power plants, the costs of fuel and, therefore, the price of coal has two opposite impacts. On the one hand, a high coal price renders investment in a technology with a higher net efficiency more attractive (note that the older power plant's efficiency is lower compared to the efficiency of a new-build CCS power plant). On the other hand, high coal prices result in an overall unattractive investment in coal-fired power plants. The comparison of the two probability plots shows that the second effect dominates, delaying the investment decision in all cases where the price of coal increases.

For new CCS plants, the influence of the electricity price is opposite to that of the coal price. For low electricity prices, the entire power plant becomes economically unattractive and so does the construction of a new CCS power plant. For a retrofit however, the probability of retrofitting a CCS-ready power plant decreases during the first periods when the electricity price increases. This is caused by the reduced electricity output causing opportunity costs for unsold electricity. For the non-capture-ready case, the electricity price acts in the opposite direction, showing that the revenues gained cannot cover the costs of the retrofit.

The influence of the carbon dioxide price and the T&S costs is depicted in Fig. 7. As expected, their influence is in the opposite direction. Important to mention is the fact that for high carbon dioxide prices, the option of retrofitting a capture-ready power plant becomes attractive before the replacement of the power plant by a new CCS plant. For all other cases, the option of retrofitting is far less attractive than the replacement option.



(a) $P_{\mathrm{coal,2015}} = 59\,€/\mathrm{t}$

(b) $P_{\mathrm{coal,2015}} = 79\,€/\mathrm{t}$

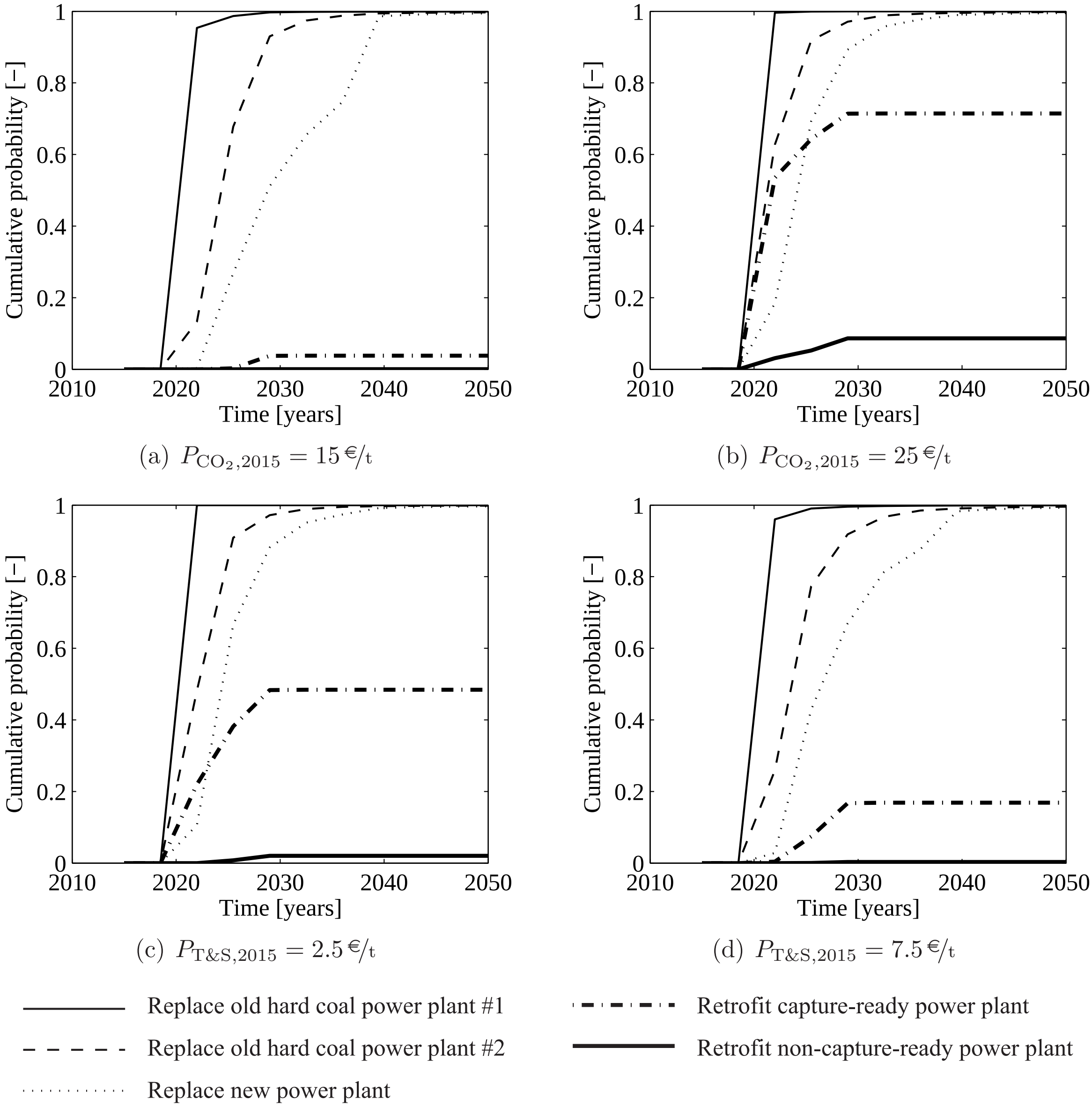
(c) $P_{\mathrm{el,2015}} = 50\,€/\mathrm{MWh}$

(d) $P_{\mathrm{el,2015}} = 70\,€/\mathrm{MWh}$

Figure 5: Influence of the coal and electricity price on the merit order of the clean-coal technology pathways.

5.3 Influence of the investment costs

The costs of retrofitting or constructing a new power plant influence the investment decision markedly. For a fifty percent increase of those costs, there is no positive probability found for retrofitting a non-capture-ready power plant. Also, the chance of retrofitting a capture-ready power plant decreases from approximately 35% to less than 10%. However, high



(a) $P_{\mathrm{CO_2},2015} = 15\,€/\mathrm{t}$

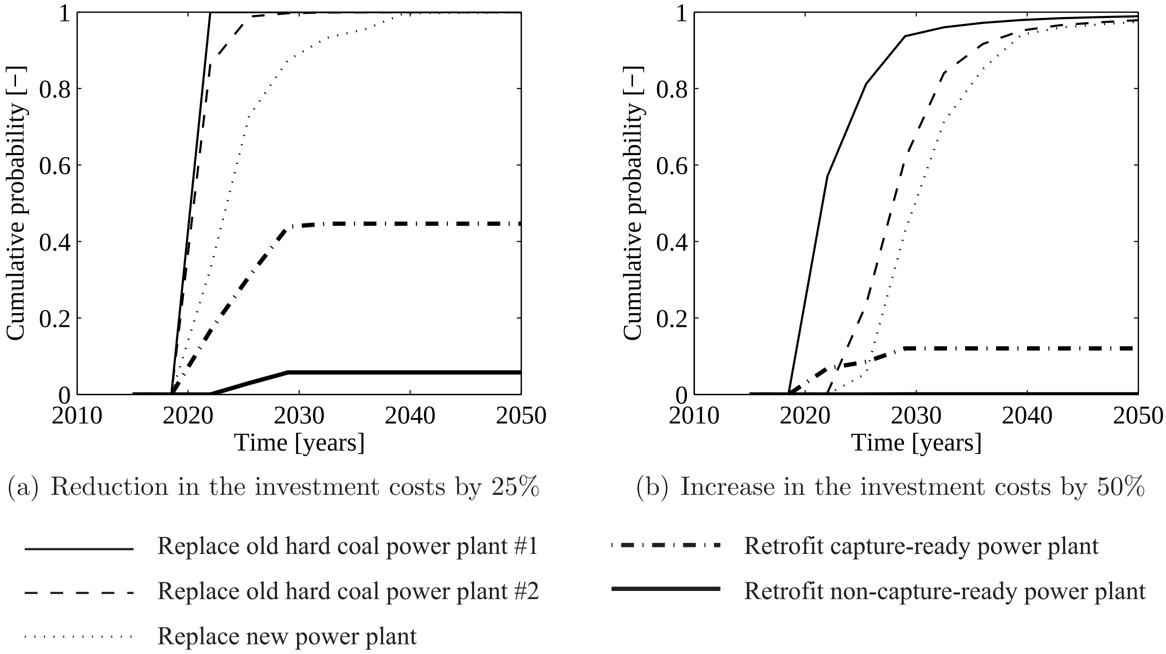
(b) $P_{\mathrm{CO_2},2015} = 25\,€/\mathrm{t}$

(c) $P_{\mathrm{T\&S},2015} = 2.5\,€/\mathrm{t}$

(d) $P_{\mathrm{T\&S},2015} = 7.5\,€/\mathrm{t}$

Figure 6: Influence of the price of carbon dioxide emission allowances and the T&S costs on the merit order of the clean-coal technology pathways.

probabilities of replacing older power plants (or the hard coal plant built in 2015) by a new CCS power plant are still found.



(a) Reduction in the investment costs by 25%

(b) Increase in the investment costs by 50%

Figure 7: Influence of the investment costs on the merit order of the clean-coal technology pathways.

6 Conclusions

This paper investigates the value of capture-readiness by examining the merit order of various clean-coal pathways in terms of the cumulative probability of adoption. To do this, we developed an enhanced and novel net present value model with technology- and path-dependent discounting based on the well-known Capital Asset Pricing Model (CAPM). The model endogenously determines the associated economic risk based on the combination of the underlying assets' prices (e.g. price of electricity, fuel, and carbon dioxide). This combination is a result of the technology-specific input and output quantities (electricity output, fuel consumption, carbon dioxide emissions) and the path-dependent prices.

Applying this model and using technical specifications from the German "Pilot Study 2010" (Nitsch et al., 2010), which provides projections for the required specifications until 2050, we find that the option of replacing older power plants including a premature shut-down with a new CCS power plant is, in the majority of investigated scenarios, found to be the preferred choice. In addition, we show that the option of replacing a new conventional coal-fired power plant (built in 2015) with a new CCS power plant is also much more likely than retrofitting a non-capture-ready or even a capture-ready power plant.

For the value of capture-readiness, we conclude that, although capture-readiness increases the chance of a retrofit strongly in comparison to a non-capture-ready power plant, the chances of conducting a retrofit are still low due to the additional option of a premature shut-down in combination with a new-build CCS power plant. Expenditures for capture-readiness should therefore be well-deliberated.

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