E.ON Energy Research Center
FCN | Institute for Future Energy
Consumer Needs and Behavior

FCN Working Paper No. 12/2013

Optimal Power Generation Investment: Impact of Technology Choices and Existing Portfolios for Deploying Low-Carbon Coal Technologies

Wilko Rohlfs and Reinhard Madlener

August 2013

Institute for Future Energy Consumer Needs and Behavior (FCN)

School of Business and Economics / E.ON ERC

RWTH AACHEN UNIVERSITY

Institute for Future
Energy Consumer Needs
and Behavior

FCN Working Paper No. 12/2013

Optimal Power Generation Investment: Impact of Technology Choices and Existing Portfolios for Deploying Low-Carbon Coal Technologies

August 2013

Authors' addresses:

Wilko Rohlfs
Institute of Heat and Mass Transfer
Faculty of Mechanical Engineering
RWTH Aachen University
Eilfschornsteinstrasse 16
52056 Aachen, Germany
E-mail: rohlfs@wsa.rwth-aachen.de

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-mail: RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de

Optimal Power Generation Investment: Impact of Technology Choices and Existing Portfolios for Deploying Low-Carbon Coal Technologies

Wilko Rohlfs

Institute of Heat and Mass Transfer, Faculty of Mechanical Engineering,
RWTH Aachen University, Augustinerbach 6, 52056 Aachen, Germany

Reinhard Madlener[1]

Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business
and Economics / E.ON Energy Research Center, RWTH Aachen University,
Mathieustrasse 10, 52074 Aachen, Germany

August 2013

---

[1] Corresponding author. Tel: +49-241-80 49 820; Fax: +49-241-80 49 829.
E-mail: RMadlener@eonerc.rwth-aachen.de (R. Madlener).

Abstract

In this paper we identify optimal strategies for the investment in power generation assets. The investments are characterized by multiple available technologies whose economic value is driven by a technology-specific combination of several underlying assets, such as the price of fuel, electricity, and CO_2. The correlation between the development of those underlying assets allows for diversification and thus to reduce the overall risk by holding a portfolio of different technologies. This yields an investor-dependent strategy for the deployment of new energy generation assets. The modeling framework developed is based on stochastic real options analysis that enables to account for the additional value of waiting which arises from uncertain commodity price development. In the presentation, we increase the model's complexity stepwise, in order to depict the influences of various aspects, as for instance the interaction of technologies, value of waiting, or modification of an existing power plant portfolio. We find that including the value of waiting in the decision process not only delays the investment but also leads to an asymmetric risk distribution which features a much lower probability for losses. In addition, the results where the value of waiting is incorporated are more robust with respect to a variation of the investor's risk- and time-preferences compared to the results gained with the classical net present value model. Finally, we investigate the required market conditions needed for the deployment of carbon capture and storage (CCS) technologies. We find that a carbon dioxide price of 60 €/$\mathrm{t}_{\mathrm{CO}_2}$ and an electricity price of 70 €/$\mathrm{MW_h}$ is required in the year 2015 in order to reach a probability of at least 50% for the deployment of CCS in 2022.

Key words: CCS; Real options; Retrofit; Renewable energies

1 Introduction

Carbon capture and storage (CCS) is seen by many international organizations (IEA, 2010; World Energy Council, 2007), the European Commission (2011a) and also by many energy modelers (e.g. Nitsch et al., 2010) to play a major role in reducing carbon dioxide emissions.

In the literature, CCS technologies are evaluated from different perspectives and by various methods. Life cycle analyses (LCA), for instance, aim to identify overall environmental consequences of technologies by examining all impacts from cradle to grave. In Pehnt and Henkel (2009), for example, the environmental impact of the post-combustion, pre-combustion and oxyfuel carbon capture processes was examined, revealing a clear benefit of the pre-combustion technology compared to post-combustion. Similar results were obtained by Zapp et al. (2012). However, most of the LCA studies remain silent about the technology's economic value.

In contrast, studies such as Davison (2007) compare the specific cost of different technologies for capturing carbon dioxide (post-combustion, pre-combustion and oxy-combustion) with those of conventional power generation plants. Typically, as a result, the cost of electricity generation, the cost of carbon capture and compression, and the cost of avoided emissions are presented. Studies with similar intention have been presented, among others, by Hammond et al. (2011) and the IEA (2011). Caused by different underlying assumptions in such cost studies (discount rate, expected life-time, operating hours, etc.) a comparison of the results is rather difficult or even unfeasible. Strong criticism has therefore been raised e.g. by Rubin (2012), not only with respect to the different assumptions made, but also according to the inconsistent definitions of important characteristic numbers such as the cost of CO_2 avoided, captured or abated.

Thus, even though a plethora of economic studies compare conventional and CCS power generation technologies, they usually do not aim at predicting the technology's potential in light of interactions with other available technologies. Due to the strong interest in CCS and its potential deployment, many studies deal with the question when this technology will become available for commercial use (for a review see Rubin et al., 2012). To address this question, technology roadmaps and deployment scenarios have often been developed by governmental (US Department of Energy, 2010; European Commission, 2011b) as well as non-governmental organizations (CSLF, 2009; Nitsch et al., 2010; EPRI, 2011). Such roadmaps or scenarios, if gained from engineering-economic energy models, typically aim at a mathematical representation of the entire energy system, e.g. electricity supply, consumption and storage, making assumptions about population growth or technological change. Most of those models are based on general equilibrium or linear optimization approaches, aiming at a cost-minimized energy mix. However, those models usually do not adequately account for effects, such as commodity prices or technical and regulatory uncertainty, which may lead to a substantial difference between the price level at which CCS becomes economically viable and the price level at which an investor will take the decision to build a CCS power plant. Hence, in our study, the possible deployment of CCS as well as the required market conditions for the latter are investigated from an investor's point of view, taking especially commodity price uncertainty into account.

In recent years, investors in power generation assets are confronted with the problem of an increasing commodity price volatility, rapid technical change, and regulatory uncertainty which render the decision more and more risky. As a consequence, stochastic model approaches and their application to the energy sector have flourished that support decision-makers with background information about optimal investment strategies. Reinelt and Keith (2007), for instance, investigate the cost of regulatory uncertainty in carbon capture retrofit investments, based on a two-dimensional model (volatile natural gas price, uncertain carbon regulation) for different coal-fired power plants using Bellman's Principle of Optimality (Bellman, 1957). However, such a separated comparison of alternative investment options is insufficient and remains silent about both the optimal timing of investment and the optimal technology mix.

Real options (RO) models (Black and Scholes, 1973; Dixit and Pindyck, 1994) are attractive in this respect as they allow to explicitly address these points by accounting for the value of waiting or postponement of the investment (McDonald and Siegel, 1986). Therefore, it is not too surprising that in recent years RO models have been increasingly applied also in the energy literature, even though most applications have only dealt with one or two technologies and a single stochastic variable at a time (typically some input fuel or the electricity price, or the difference between the two – the "spread").

In a former study of the authors (Rohlfs and Madlener, 2013a), the influence of carbon capture readiness was investigated by a stochastic NPV model with an endogenous, time- and technology-dependent discount rate. With this model, the value of carbon capture readiness was found to be small and the option of replacing older power plants – including a premature shut-down – with a new CCS power plant turned out to be the preferred choice in the majority of investigated scenarios.

The original contribution of this paper is threefold: First, the development of a model is presented which allows to estimate the probability to invest in a specific technology in the future, thereby accounting for various aspects. This includes the effect of technology-specific risk emerging from a technology-specific combination of underlyings (e.g. price of electricity, fuel, and carbon dioxide allowances), the effect of exogenously prescribed technical innovation/learning as well as the effect of multiple existing and concurring technologies. Still another effect included is the above-mentioned value of waiting. Finally, the model accounts for the influence of an investor's existing power plant portfolio on the investment decision. The second original contribution of this paper is the analysis of the influence of the previously mentioned effects by a stepwise increase of the model's complexity, while retaining the value of the underlying parameters. The third contribution is the application of the model for identifying market conditions (e.g. bounds for the price of electricity and carbon dioxide allowances) for which the deployment of CCS becomes highly probable in the near future.

The remainder of this paper is structured as follows. Section 2 introduces the modeling framework, while Section 3 reports on the underlying data and assumptions used. Section 4 presents the results and Section 5 concludes.

2 Problem analysis and modeling approach

Investors in the electricity supply industry are spoilt for choice of deciding from one of various available technologies when investing in new power generation units. Both the fuel type (hard-coal, lignite or gas-fired) and also the possible implementation of carbon mitigation technologies allow a variety of technological options. Due to the capital-intensiveness and the long life-time of new power generation units, single investment decisions (in a new power plant and thus in a portfolio modification) have a strategic character and may have strong implications on the investor's future performance.

In a broad examination of a power plant, the economic value results from the specific cost of investment, operation and maintenance cost, and technology-specific parameters which determine the incoming and outgoing cash flows during the power plant's lifetime – such as the electricity production, fuel consumption, CO_2 emission, and average annual utilization.

In a classical and simple valuation method, the net present value (NPV) of a power plant is calculated based on future cash flows, which result from deterministic price paths, and by a predefined discount rate. The value of the predefined discount rate is either chosen based on experienced data or calculated based on methods like the "average cost of capital". With a broad variation of the deterministic price paths, the risk associated with the investment can be estimated.

However, if different technologies are compared with each other, the associated economic risk varies between the technologies. This is caused by a different combination of inputs and outputs, and consequently their cash flows. On the one hand, the combination of those resulting cash flows depends on the technology-specific mass- and energy flows (e.g. fuel consumption and electricity output), and, on the other hand, on the development of the underlying prices (e.g. price of electricity, fuel, and CO_2). This price development can be described by correlated stochastic processes (similar as in portfolio theory; Markowitz, 1952, 1991). For example, a rising commodity price of a risky asset increases the risk of a technology being strongly dependent on this asset.

In order to consider the differences in risk, we have developed a multi-dimensional model on the basis of correlated stochastic price processes which accounts for the uncertain distribution of future cash flows. The underlying stochastic price processes are represented by Geometric Brownian Motions (GBM), the most commonly used stochastic process (see also Dixit and Pindyck, 1994; Hull, 2005), with constant growth rates α_k and volatilities σ_k, yielding

$$\frac{dP_k(t)}{P_k(t)} = \alpha_k dt + \sigma_k dZ_k, \tag{1}$$

where dZ_k are increments of correlated Gauss-Wiener processes, so that the expected value is $E[dZ_k dZ_j] = \rho_{kj} dt,\ k \neq j$; ρ_{kj} denotes the correlation between process k and process j.

As an illustration, Fig. 1 (left plot) shows ten sample paths of the electricity price development calculated by a Monte-Carlo simulation of eq. (1). In addition, the analytically given mean value as well as the σ-confidence interval are depicted for the parameters reported in Table 1. Figure 1 (right plot) shows the correlation between the electricity price and the coal price in $t = 2050$ for a correlation coefficient of $\rho_{\text{el,coal}} = 0.608$.

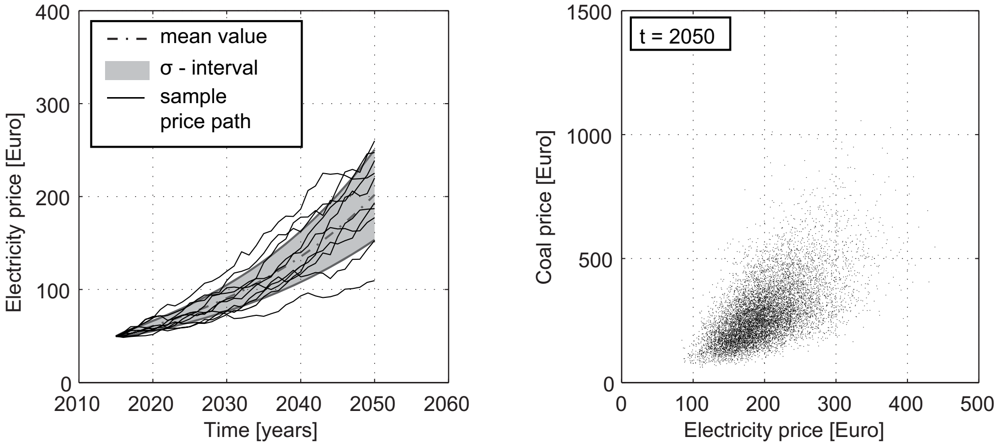

Figure 1: Sample paths of the price development (left plot) and correlation between two assets (coal and gas) in $t = 2050$ (right plot), both calculated by Monte-Carlo simulation technique.

The distribution[1] of the future cash flows is thus given by the inner product of

$$\mathbf{CF}(t) = \vec{\mathbf{P}}(t) \cdot \vec{Q}(t_{\text{d}}, t), \tag{2}$$

where $\vec{\mathbf{P}}(t)$ denotes the n-dimensional price vector and $\vec{Q}(t_{\text{d}}, t)$ the in- and outflow of mass and energy. The latter depends on the time of the investment t_{d} and on the actual time t. The dependence on t_{d} allows a consideration of technological progress such as an increase in net efficiency. The actual time t might account for a reduction in the average utilization, for instance caused by an increasing share of renewable energy sources.

Based on the time of the investment, the projected lifetime of the power plant t_{LT}, and the cost of investment I_i, the NPV of a specific investment, i, yields

$$\mathbf{NPV}_i(t_{\text{d}}) = \int_{t_{\text{d}}}^{t_{\text{d}}+t_{\text{LT}}} \vec{\mathbf{P}}(t) \cdot \vec{Q}_i(t_{\text{d}}, t) \cdot e^{-\delta \cdot t} dt - I_{\text{i}}(t_{\text{d}}). \tag{3}$$

The discount rate δ reflects the investor's expected return on investment. The distribution of the NPV characterizes the uncertainty of the investment. Assuming a perfect

---

[1] In this paper, we type stochastically distributed variables in boldface.

scalability, the investor's decision only depends on the risk structure and not on the size of the power plants. With this assumption, we can introduce a relative NPV distribution (similar to a "return on investment") as

$$\mathbf{RNPV}_i(t_\mathrm{d}) = \frac{\mathbf{NPV}_i(t_\mathrm{d})}{I_i(t_\mathrm{d})}. \tag{4}$$

With this scaling, the investor's requested rate of return, δ, is met if $\mathbf{RNPV}_i$ is zero. A positive $\mathbf{RNPV}_i$ denotes that the expected rate of return is exceeded. In contrast, a negative value of -1 characterizes a total loss of the investment for which $\mathbf{NPV}_i = -I_i$. Note that values below -1 are possible; for instance if contracts have to be fulfilled forcing the owner of the power plant to operate even if variable costs exceed revenues.

The distribution function of the relative NPV is the basis of the investment decision. However, rating the distributions of different technologies is rather difficult. Thus, a utility function is introduced. With this function, the behavior of the investor in terms of risk aversion can be modeled for the decision process as

$$U(\mathbf{RNPV}_i) = \overline{\left(\Theta\left(-\mathbf{RNPV}_i\right) + a \cdot \Theta\left(\mathbf{RNPV}_i\right)\right) \cdot \mathbf{RNPV}_i}, \tag{5}$$

where $0 < a < 1$ is an investor-specific parameter modeling the risk-averse behavior and $\Theta(x)$ is the Heaviside-function (or unit step function) which approaches one if $x \leq 0$ and zero if $x < 0$.

Based on the described methodology, different decision rules – in the order of increasing complexity – are outlined in the following three sub-sections.

2.1 Net present value based investment decisions

The most simple decision rule is to calculate the value of the utility function for each technological option i and to decide for the investment which maximizes the relative benefit, i.e.

$$\max(U(\mathbf{RNPV}_i), 0). \tag{6}$$

The additional value of zero represents the option to refrain from investing which is preferable if the average NPV of all investments is negative.

For today's investment decision, the price vector $\vec{P}(t=0)$ is deterministically given. This yields a unique value for the investment decision. From the present point of view, the returns of a future investment decision start with the initial price vector $\vec{\mathbf{P}}(t_\mathrm{d})$ being a stochastically distributed measure. This results in a stochastically distributed investment decision with a probability to invest in a specific technology in the future.

2.2 The value of waiting

From real options theory it is well known that the opportunity to postpone an investment can increase the investor's financial value even if the NPV leads already to a positive investment decision ("option to wait", see McDonald and Siegel, 1986). The reason for this increasing value is found in the flexibility and the additional information which the investor gains from waiting. For the case that the prices move in a favorable direction for a specific technology, the investment is undertaken. For the case that the prices move in a non-favorable direction another technology is chosen or no investment is made. Obviously, the value of waiting increases with the flexibility of the investor and thus with the number of available technologies. Another cause for the value of waiting is technical innovation, also integrated in our model. Strictly speaking, it is favorable to wait if the discounted value of the delayed investment surpasses the value of an immediate investment.

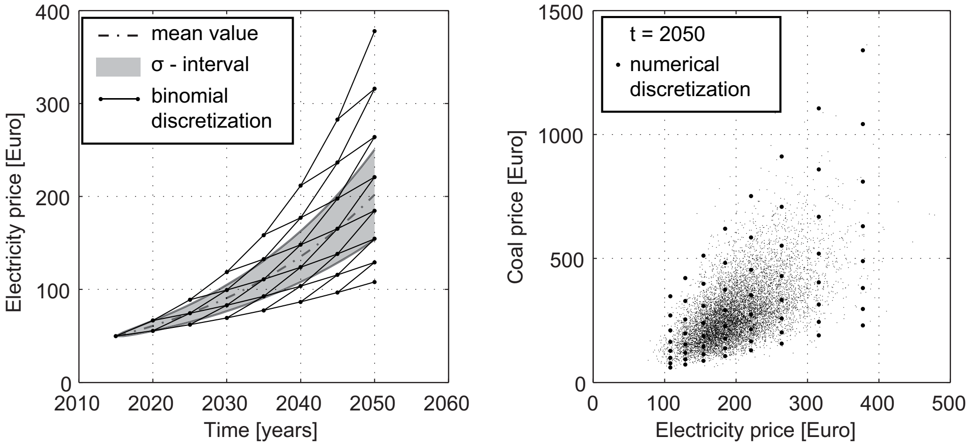

Figure 2: Multi-dimensional lattice approximation of the correlated stochastic processes.

In order to account for the value of waiting, it is necessary to know the value of future investments. This value includes the possibility of a further delay and is thus dependent on the values of the subsequent period. Thus, the entire decision problem has to be solved recursively up to a point in time where the option is assumed to expire. In this work, a multi-dimensional lattice method is applied, as described in Rohlfs and Madlener (2011a) and Rohlfs and Madlener (2013b). The model solves the problem recursively, beginning with a final point in time t_{end}. Such a lattice approach approximates the continuous stochastic processes (see eq. (1)) by a finite number of upward and downward jumps. Figure 2 illustrates the discretization by the multi-dimensional lattice method for the same stochastic processes as the ones depicted in Fig. 1. Note that the position of the sampling points is adjusted by the correlation between the two assets according to Rubinstein (1994). This avoids negative probabilities as it is often a problem in higher-dimensional lattice methods (Gamba and Trigeorgis, 2007; Abadie et al., 2013).

While the option value at each final node can be calculated from eq. (4), preceding nodes need to account for the value of waiting, which arises from all subsequent nodes, k, as

$$\mathbf{RVoW}(t) = \sum_k \left[\frac{\mathbf{NPV}_i^*(t+1)}{I_i^{\times}(t+1)} \right]. \tag{7}$$

It is worthwhile to mention that the investment costs are not discounted by the expected rate of return δ. For this discounting a rate of return is used reflecting the investor's yields in the meantime. This rate of return can, for instance, be represented by the return of a secure asset such as government bonds. Contrary, the NPV of the investment is reduced via the investor's expected rate of return δ. This approach is necessary because otherwise the numerator as well as the denominator would be discounted by the same rate δ. Consequently, the discounting would disappear, leading to a vanishing cost of waiting and a maximum delay of the investment.

With eq. (7), the decision rule (6) is extended for all nodes preceding the final ones to

$$\max(U(\mathbf{RNPV}_{\mathrm{i}}), U(\mathbf{RVoW}), 0). \tag{8}$$

2.3 Optimal portfolio extension

The decision rules described so far treat the investment detached from the investor's existing fleet of power plants. However, the investment decision can be significantly influenced by the correlation between the performance of the new investment and the existing portfolio. Due to this correlation, the systematic (counteracting) risk vanishes. For instance, a utility company owing mostly gas-fired power plants would favor an investment in a coal-fired power plant much stronger due to diversification effects compared to a company whose portfolio consists mainly of coal-fired power plants.

In order to account for the existing power plant fleet the relative NPV is augmented by the net cash flows of the existing portfolio and the actual cash value of the fleet. This yields a combined relative NPV of new and existing power plants

$$\mathbf{RNPV}_{i+\text{Base}} = \frac{\mathbf{NPV}_i + \mathbf{NCF}_{\text{Base}} - V_{\text{Base}}}{I_i + V_{\text{Base}}}. \tag{9}$$

The utility of the new investment is determined by subtracting the utility of the base fleet from the utility of the entire portfolio as

$$U(\mathbf{RNPV}_i) = \frac{U(\mathbf{RNPV}_{i+\text{Base}})(I_i + V_{\text{Base}}) - U(\mathbf{RNPV}_{\text{Base}})(V_{\text{Base}})}{I_i}. \tag{10}$$

Considering the option to delay the investment decision, the relative value of waiting is

$$\mathbf{RVoW}(t) = \sum_k \left[\frac{[\mathbf{NPV}_i(t+\Delta t) + \mathbf{NCF}_{\text{Base}}(t+\Delta t)]\, e^{-\delta \Delta t} - V_{\text{Base}}(t) + \int\limits_t^{t+\Delta t} \mathbf{CF}_{\text{Base}} e^{-\delta t} dt}{I_i(t+\Delta t)e^{-\gamma \Delta t} + V_{\text{Base}}(t)} \right]. \tag{11}$$

The last term in the numerator considers the cash flows between t and $t + \Delta t$. Equations (6) and (8) remain unchanged for the optimal investment decision.

3 Underlying technical and economic data

The following section briefly summarizes the economic and technical boundary conditions assumed in this study (for more details see Rohlfs and Madlener, 2011a). The price pro-

Table 1: Parametrization of the price processes

Parameter	$P_{i,0}$ [€]	α_i	σ_i	$\rho_{i,\mathrm{el}}$	$\rho_{i,\mathrm{coal}}$	$\rho_{i,\mathrm{gas}}$	$\rho_{i,\mathrm{CO_2}}$	$\rho_{i,\mathrm{M}}$
P_{el}^{a}	49.8	4.00%	4.00%	1.000	0.608	0.695	0.498	0.141
P_{coal}^{b}	69	4.18%	7.09%	0.608	1.000	0.593	0.239	0.254
P_{gas}^{c}	7.2	4.03%	6.70%	0.695	0.593	1.000	0.258	0.156
$P_{\mathrm{CO_2}}^{d}$	20	4.14%	7.07%	0.498	0.239	0.258	1.000	0.192
P_{M}^{e}	1	2.00%	2.00%	0.141	0.254	0.155	0.192	1.000

Notes: ^{a}base-load futures traded at the EEX (F1BY, July 1, 2002 - February 18, 2013); ^{b}coal futures traded at the EEX (FT4Y, May 2, 2006 - January 18, 2012); ^{c}natural gas futures traded at the EEX (G0BY, July 2, 2007 - February 18, 2013); ^{d}EUA price (F2PE & F2EA, October 4, 2005 - February 18, 2013) at the EEX. ^{e}German stock index (DAX, March 2, 1992 - February 18, 2013).

jections for electricity, coal, natural gas and carbon permits were calculated based on the predictions of the so-called German Pilot Study 2010 (Nitsch et al., 2010). The correlation coefficients are estimated based on historical price data provided by the European Energy Exchange (EEX) in Leipzig for electricity, coal, and natural gas as well as the emission allowances of the European Union Emissions Trading System (EU ETS) . Table 1 summarizes the economic data used for the analysis.

3.1 Specifications of the available technologies

Table 2 summarizes the technological data used which refer to the German Pilot Study 2010 (Nitsch et al., 2010) providing projections until 2050 . However, it is worthwhile to note that high uncertainty exists in the cost estimate for a technology that has not yet been built, operated and replicated on a commercial scale (Rubin et al., 2012). In order to allow for a comparison of the different technologies, we decided to base our analysis on the investment in a power plant with an electricity generation capacity of $500\,\mathrm{MW_{el}}$. Fuel consumption (if any) is calculated by the given net efficiency and the assumed specific energy contents of the fuel ($30\,^{\mathrm{MJ}}/_{\mathrm{t}}$ for hard coal and $8\,^{\mathrm{MJ}}/_{\mathrm{m^3}}$ for natural gas). The cost of transporting and storing CO_2 (additionally occurring for the CCS technologies with an absorption rate of 90%) is assumed to be $4\,^{€}/_{\mathrm{t_{CO_2}}}$ thus following McCoy (2008). For the escalation of the transporting and storing cost of CO_2 the market development has been assumed.

Table 2: Power plant data according to the German Pilot Study 2010

Name, **acronym**, O&M cost, lifetime	Parameter	Unit	Year				
			2015	2020	2030	2040	2050
Onshore wind, **ONW**, 4% Investment/a, 18 a	average utilization	h/a	2100	2200	2350	2450	2550
	specific invest. cost	€/kW$_\mathrm{p}$	1180	1030	980	940	900
Hard coal, **HC**, 2% Investment/a, 25 a	efficiency	–	47	50	51	51	51
	average utilization	h/a	5000	5000	5000	5000	5000
	specific invest. cost	€/kW$_\mathrm{p}$	1300	1300	1300	1300	1300
	CO$_2$ emissions	kg/MWh$_\mathrm{el}$	656	620	609	609	609
Hard coal Integrated Gasification Combined Cycle, **HC-IGCC** 2% Investment/a, 25 a	efficiency	–	–	52	54	54	54
	average utilization	h/a	–	5000	5000	5000	5000
	specific invest. cost	€/kW$_\mathrm{p}$	–	1500	1500	1500	1500
	CO$_2$ emissions	kg/MWh$_\mathrm{el}$	–	598	577	577	577
Hard coal Integrated Gasification Combined Cycle with CCS, **HC-IGCC-CCS** 2% Investment/a, 25 a	efficiency	–	–	43	45	45	45
	average utilization	h/a	–	5000	5000	5000	5000
	specific invest. cost	€/kW$_\mathrm{p}$	–	2200	2200	2200	2200
	CO$_2$ emissions	kg/MWh$_\mathrm{el}$	–	107	102	102	102
Combined gas and steam **COGAS**, 2% Investment/a, 25 a	efficiency	–	59	60	62	62	62
	average utilization	h/a	5000	5000	5000	5000	5000
	specific invest. cost	€/kW$_\mathrm{p}$	700	700	700	700	700
	CO$_2$ emissions	kg/MWh$_\mathrm{el}$	336	330	320	320	320
Combined gas and steam with CCS, **COGAS-CCS** 2% Investment/a, 25 a	efficiency	–	–	50	52	52	52
	average utilization	h/a	–	5000	5000	5000	5000
	specific invest. cost	€/kW$_\mathrm{p}$	–	1100	1100	1100	1100
	CO$_2$ emissions	kg/MWh$_\mathrm{el}$	–	59	57	57	57

Source: Nitsch et al. (2010), own compilation

4 Results

The results presented in this section are divided into two parts. The first part (section 4.1) outlines the investment decision in coal- and gas-fired power plants with and without CCS using the different decision rules. In the second part (section 4.2), variations of the electricity and coal price are performed in order to identify the most preferable market conditions for a deployment of carbon capture technologies.

4.1 Influence of the decision rules

In the following subsections, the investment decision is examined for a risk-neutral investor, implying a linear transformation of the relative NPV by the utility function, e.g. $a = 0$ in eq. (5). A discount rate of $\delta = 10\%$ is assumed to hold for the investor's time preference in the evaluation procedure of all technologies. The influence of both assumptions, the risk-neutral investor and the assumed discount rate, will be validated and discussed at the end of this subsection.

4.1.1 NPV-based investment decisions

In the case of the NPV-based investment decision, the average expected NPV from (6) is used for deciding whether to invest or not.

“Now or never” – building a power plant today

The plots in Fig. 3 show the distribution of the expected NPV for the investment in a conventional hard coal-fired (**HC**, left plot) power plant and a combined gas and steam (**COGAS**, center plot) power plant for the case of an investment in $t = 2015$. Because of the low price for electricity and the high costs for fuel and emission allowances, negative NPVs dominate for both technologies, rendering an investment very unattractive. While the distribution for the coal-fired power plant is more or less Gaussian-like, the distribution of the gas-fired power plant shows a clear drop-off below a NPV of €450 million. The drop-off is caused by the possibility of abandoning the power plant if the costs of electricity production overcome the revenues from the electricity sale. In this case, only the expenditures for operation and maintenance are assumed to cause further costs. A different representation of the two probability distributions is given in the right-hand plot of Fig. 3. Here, the cumulative distribution allows a direct comparison of the two technologies. The cumulative probability shows that the probability of a positive NPV is less than 10% for the **HC** power plant and even lower for the **COGAS** power plant. Note that a positive NPV means that the expected rate of return ($\delta = 10\%$) is achieved. Thus, a negative NPV does not necessarily imply that the investor suffers from losses of the investment.

“Now or never” – tracking the decision into the future

The investor’s decision rule to invest in a new power plant as soon as the average NPV turns positive can also be investigated for subsequent time periods ($t > 2015$). In line with the assumption that the prices of the subsequent periods follow correlated stochastic processes, the probability to invest in a future state can be estimated. Figure 4 depicts the distribution of the expected value discounted to the time $t = 2015$. In addition to

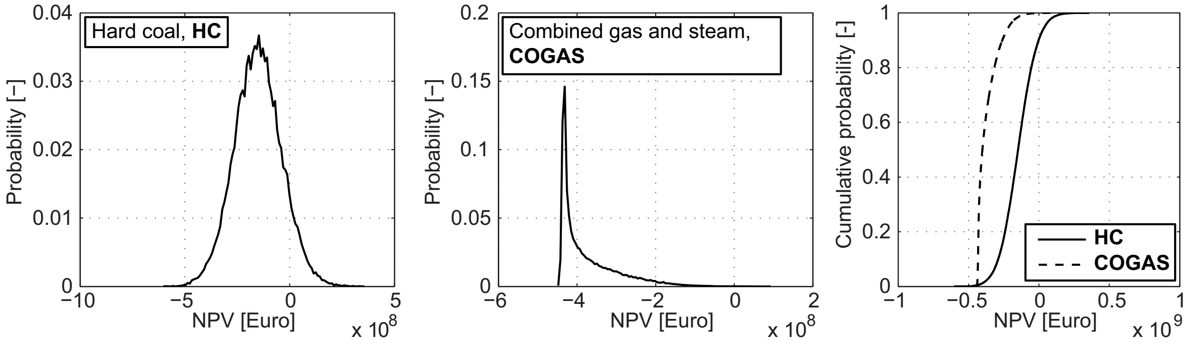

Figure 3: Probability density plot of the NPV for an investment in a conventional hard coal (**HC**, left plot) and a combined gas and steam power plant (**COGAS**, center plot) in 2015. The cumulative probability plot (right plot) compares the distribution of the NPV of both investment options.

the **HC** and the **COGAS** power plant, the technologies with carbon capture and storage are considered. These technologies include hard coal-fired integrated gasification combined cycle with carbon capture and storage (**HC-IGCC-CCS**) and combined gas and steam with carbon capture and storage (**COGAS-CCS**).

For this decision rule, the overall discounted NPV in 2015 is supposed to be zero. This is because the investment is undertaken as soon as the average NPV in each period turns out to be positive. However, the simulation results show non-zero but still positive values. This deviation from the expected behavior is caused by the finite time discretization, which cannot capture the exact point in time where the average NPV surpasses zero. If more steps in the decision process would be considered, this value would reduce and approach zero[2]. Similar to the distribution of the **HC** investment in the previous subsection, the shape of the distribution is Gaussian-like with tails on both sides.

The cumulative NPV (Fig. 4, upper right plot) shows a different maximum/end value for the four technologies considered. This end value indicates the overall probability to invest in this technology within the next 35 years. The difference between this probability and the value of unity indicates the possibility of future price paths for which the investment does not achieve the desired rate of return. The probability for a future investment is also shown in Fig. 4 (lower right plot), depicting the probability to invest in one of the four technologies over time. With the assumption that only one power plant of a kind

---

[2] Due to the limitation in computational memory, the maximum possible number of time steps was found to be nine using a state-of-the-art computer (8 GB memory).

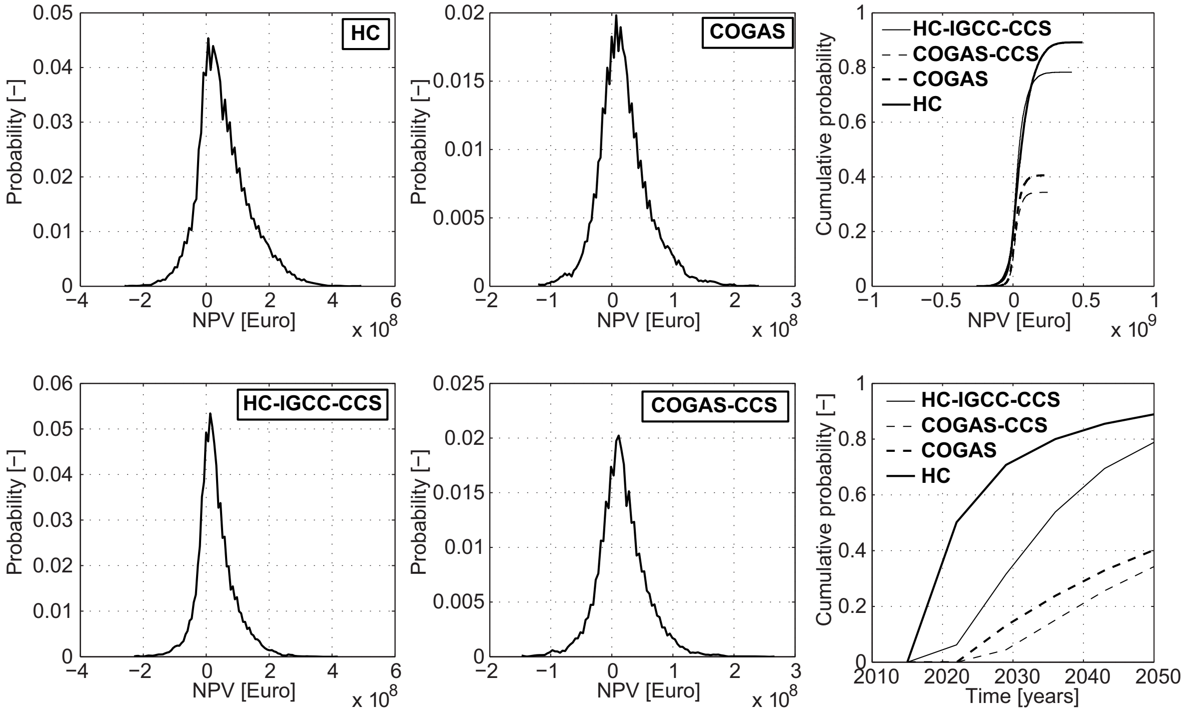

Figure 4: Probability density plots of the NPV$_{t=2015}$ (left and center plots) for the four different technologies with mean NPVs of: $\overline{\mathbf{NPV(HC)}}$ = €53 million, $\overline{\mathbf{NPV(HC-IGCC-CCS)}}$ = €26 million, $\overline{\mathbf{NPV(COGAS)}}$ = €9 million, $\overline{\mathbf{NPV(COGAS-CCS)}}$ = €7 million. The top right plot depicts the cumulative probability of the NPV, and the lower right plot the cumulative probability to invest in a technology over time.

is eventually built, price paths following a positive investment decision are not considered for a further investment. In this plot a clear dominance of the **HC** power plant can be seen for the price development that has been assumed. For both coal-fired power plants – conventional **HC** and **HC-IGCC-CCS** – the probability to invest rises above 90 percent. Caused by the high gas price, the **COGAS** and **COGAS-CCS** power plant's probability is only approximately 40 percent. Note that all four power plants are treated as base-load power plants, rendering gas-fired power plants as generally less attractive.

The value of a technology portfolio

In the previous paragraph, the four technologies have been investigated separately from each other. However, if an investor has the opportunity to build one of the four power plants, the decision behavior might change. Because of the **HC** power plant's dominance for the given initial prices, this technology will be chosen in the majority of price paths

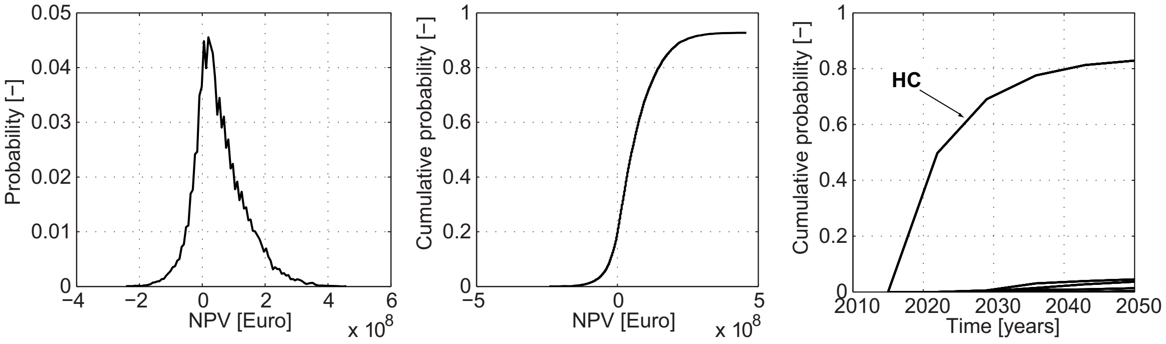

Figure 5: Value of a technology portfolio: Probability distribution of the NPV (left plot) and cumulative probability distribution (center plot) with $\overline{\mathbf{NPV(all)}}$ = €54 million. The right plot depicts the cumulative probability to invest over time.

(see Fig. 5, right plot). The other technologies have only a small influence on price paths where the **HC** power plant turns out to be non-profitable, leading to a slight increase of the cumulative probability to invest. The probability to fall below the expected rate of return is found to be less than 20 percent. The strongly reduced probability to invest for the other three technologies by the dominance of the **HC** power plant is an important finding for expenditures in R&D. If technologies are evaluated separately, they can be attributed with a high chance of a later deployment. However, as soon as technologies are examined in competition with each other, a more realistic potential can be estimated.

Optimal portfolio extension

Note that the investment strategy for an optimal portfolio extension in the case of a risk-neutral investor does not differ from the investment decision without existing power plants. Due to the linear transformation between the NPV and its associated utility, the influence of the existing power plant fleet can be separated from the new power plant. The case of a risk-averse investor in which the existing power plant does play a role in the decision process is considered later.

4.1.2 The value of waiting

After having examined the investor's behavior based on the simple decision rule (invest if $\overline{\mathbf{NPV}} > 0$), now the additional "value of waiting" (see eq. (8)) will be considered which is known to increase the investor's return.

Building a power plant in the future

Figure 6 shows the results including the value of waiting for the same cases as they were plotted in Fig. 4. Comparing both figures, a significant difference in the shape of the four probability distributions for the NPV can be detected.

While the distributions in Fig. 4 are more or less Gaussian-like, a strongly asymmetric probability distribution is found in Fig. 6, for which the probability of negative NPVs is considerably reduced. A further difference is found in the cumulative probability distribution for investment in the different technologies (Fig. 6, bottom right). Here the investment decision is clearly postponement into the future. Interestingly, despite the postponement a significant increase in the average NPV is found. For the **HC** power plant, for instance, the average NPV raised from €53 million to €68 million.

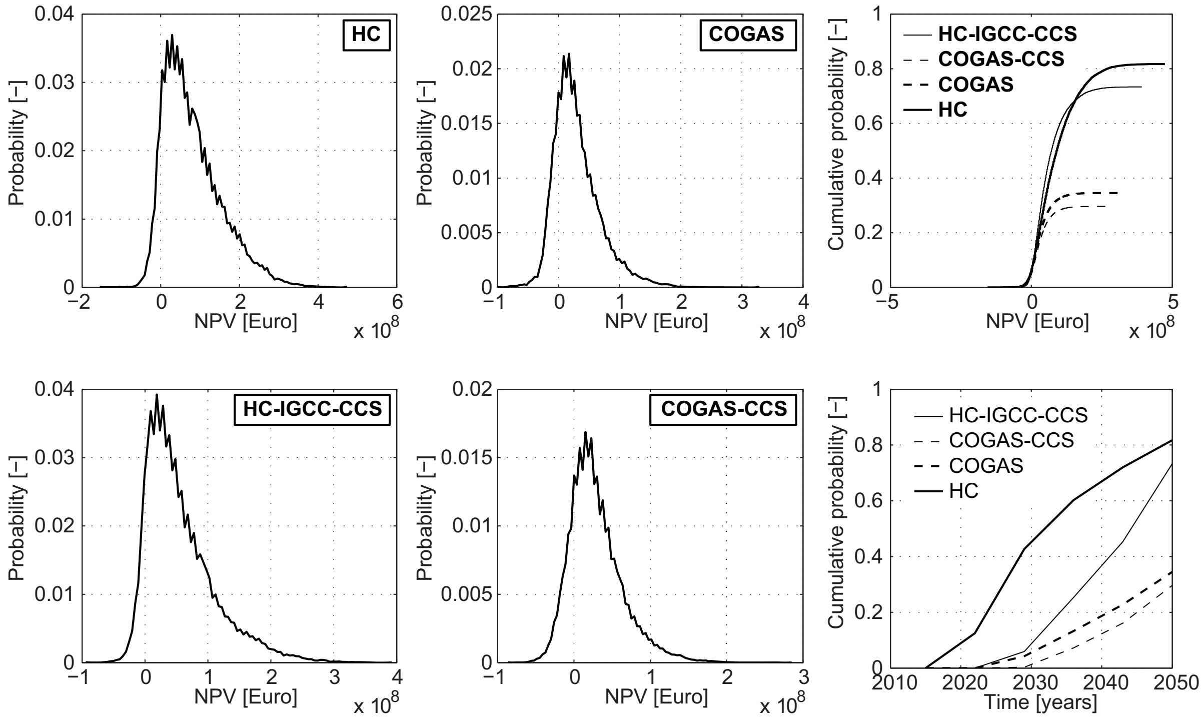

Figure 6: Probability density plots of the $\mathrm{NPV}_{t=2015}$ (left and center plots) for the four different technologies with mean NPVs of: $\overline{\mathbf{NPV}(\mathbf{HC})}$ = €68 million, $\overline{\mathbf{NPV}(\mathbf{HC}-\mathbf{IGCC}-\mathbf{CCS})}$ = €43 million, $\overline{\mathbf{NPV}(\mathbf{COGAS})}$ = €11 million, $\overline{\mathbf{NPV}(\mathbf{COGAS}-\mathbf{CCS})}$ = €9 million. The top right plot depicts the cumulative probability of the NPV and the lower right plot the cumulative probability to invest in a technology over time.

The value of a technology portfolio

Figure 7 shows the results considering the investor's choice to build one of the four available power plants and his option to postpone the investment. In comparison to the previous results, the negative values of the NPV distribution are further reduced. The probability of falling below the desired rate of return ($\delta = 10\%$) is approximately 6% according to the cumulative probability plot. Note that if the value of waiting is not considered, this probability was found to be approximately 20%. The cumulative probability to invest in the various technologies is also increased by the value of waiting. Compared to Fig. 5 (right plot), the probability of **COGAS** and the CCS-technologies increases, while the overall probability of an investment in a conventional **HC** power plant decreases.

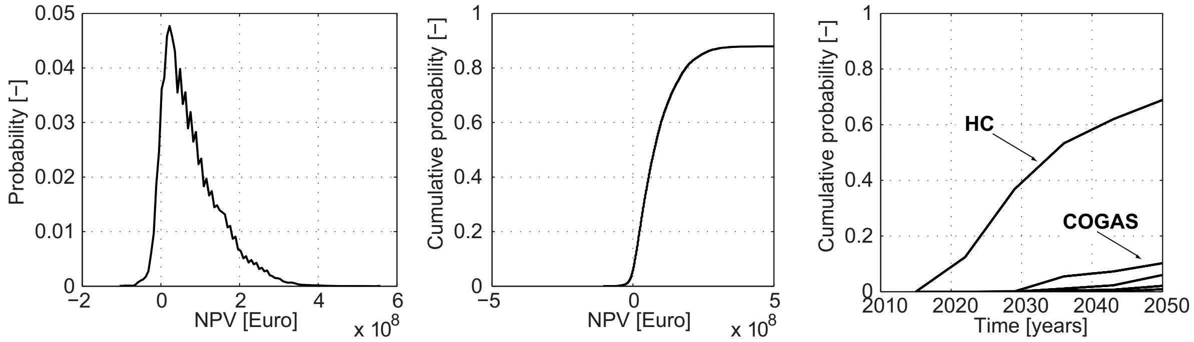

Figure 7: Value of a technology portfolio including the "value of waiting": Probability distribution of the NPV (left plot) and cumulative probability distribution (center plot) with $\overline{\mathbf{NPV(all)}} = €71$ million. The right plot depicts the cumulative probability to invest over time.

4.1.3 Optimal portfolio extension

For the optimal portfolio extension it is assumed that the investor has either a fleet of coal-fired power plants, a fleet of gas-fired power plants or a fleet of onshore wind farms (**ONW**). For all three cases, the size of the existing power plant fleet is either 500 MW_{el} or 5000 MW_{el}. For consistency, the specifications of the existing power plants are in line with the data from Table 2. To accord with the data provided in the German Pilot Study 2010 (Nitsch et al., 2010), the existing power plants are assumed to be built in $t = 2015$. The cash value of the existing power plant fleet is considered to decrease linearly over the power plant's life-time.

Figure 8 shows the cumulative probability to invest in the various technologies for the

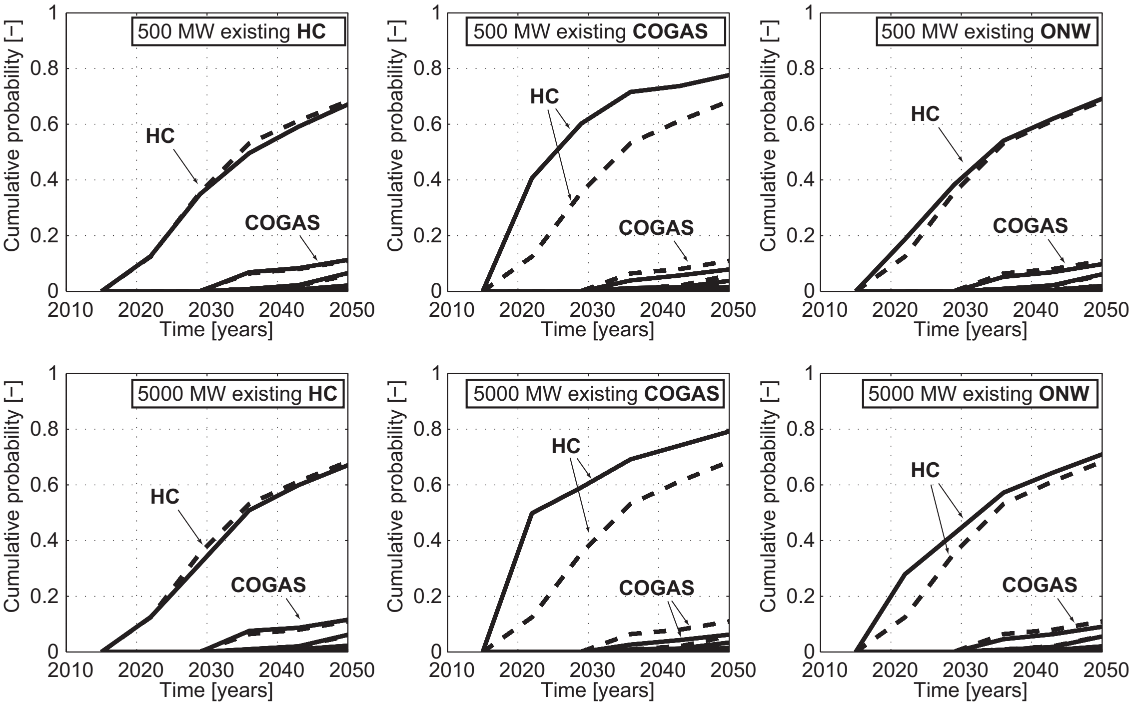

Figure 8: Influence of existing power plants on the investment decision of a risk-neutral investor when taking the value of waiting into account. The dashed lines indicate the investment decision for the case of no pre-existing portfolio.

six cases. For the case of existing **HC** power plants, only a minor deviation from the prior decision behavior (without an existing portfolio) is found. Contrary, the existing **COGAS** power plants strongly influence the investment decision, bringing the investment forward in time. A similar but weaker influence is found for existing **ONW**. Due to the limited life-time of the existing power plants, the investment decision in the last two time steps is not influenced.

The reason for the strong influence on the value of waiting by the **COGAS** power plants is the reduced volatility emerging from the correlations between the different technologies. Similar as in portfolio theory the opposing risk of the new power plant is compensated by the existing ones. This reduces the uncertainty of the future investment and thus the value of waiting. Note that due to the fact that a risk-neutral investor is considered here, the investment decision does not depend on the volatility of the expected NPV. Thus, the classical principle of diversification does not play any role. The effect of the existing power plants is solely a reduction in the value of waiting.

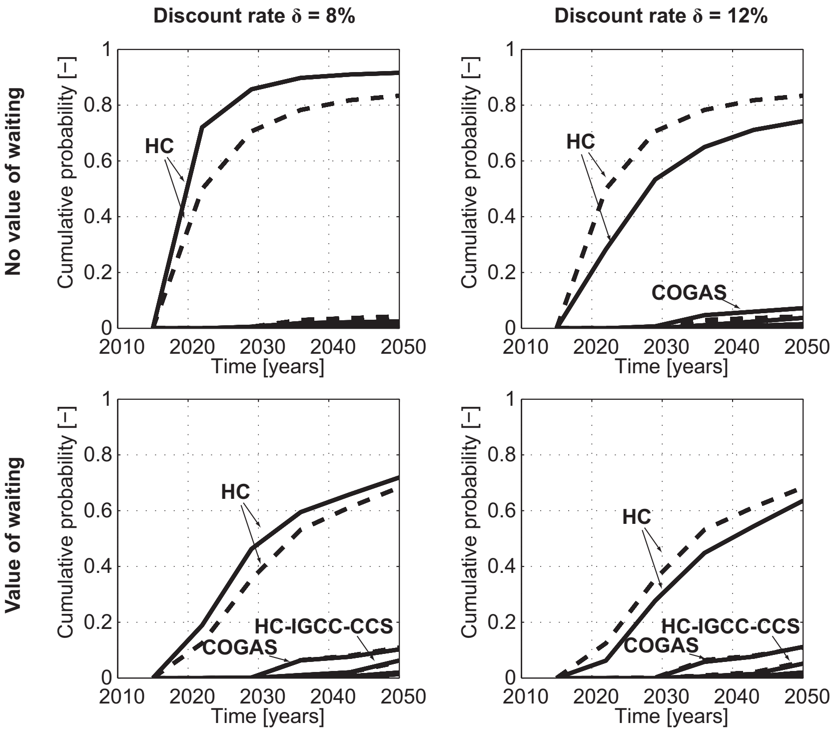

Figure 9: Influence of the investor's time-preference on the investment decision of a risk-neutral investor with and without accounting for the value of waiting. The dashed lines depict the solution for the reference case with $\delta = 10\%$.

Influence of the investor's risk- and time preferences

All prior investment decisions are based on a risk-neutral investor with a discount rate of 10%. Because both assumptions are known to largely influence the investment decision, the following paragraph contains a variation of both parameters.

Figure 9 shows a variation of the discount rate, e.g. $\delta = 8\%$ and $\delta = 12\%$, respectively. For the case that the value of waiting is not considered (upper two plots) the probability to invest in a **HC** power plant increases strongly in the first periods for $\delta = 8\%$ and decreases for $\delta = 12\%$. For $t = 2022$, the cumulative probability varies by approximately ±20%. The influence of time-discounting decreases significantly as soon as the value of waiting is included in the decision process. Here, the maximum variations are less than ±10% for **HC** power plants. In addition, the probabilities for the other technologies are only marginally influenced by the choice of the discount rate.

In order to account for a risk-averse attitude of the investor, the slope of the utility function is reduced in the region of positive NPVs compared to the region of negative

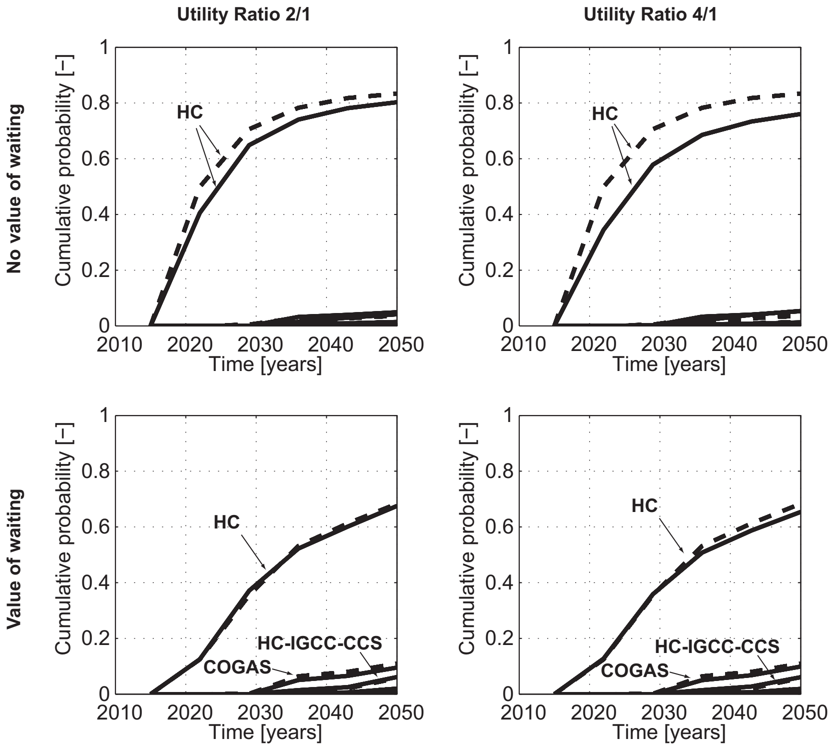

Figure 10: Influence of the investor's risk aversion on the investment decision with and without accounting for the value of waiting. The dashed lines depict the solution for the reference case of a risk-neutral investor.

NPVs. Due to the linear piecewise utility function assumed, the absolute slope does not influence the investment decision. Thus, the only influencing parameter in this function is the ratio between the slope in the positive and negative NPV region.

Figure 10 depicts the results for a utility ratio of 2 and 4, with and without the value of waiting. If the value of waiting is not considered (upper two plots), the investment decision is postponed with an increasing ratio between the two slopes. Despite the postponement of the investment decision, the average NPV increases slightly from $\overline{\mathbf{NPV}}$ = €52 million (ratio 1) to $\overline{\mathbf{NPV}}$ = €59 million (ratio 2) and $\overline{\mathbf{NPV}}$ = €63 million (ratio 4). If the value of waiting is considered, the influence of the investor's risk aversion becomes less dominant, as shown by Fig. 10 (two lower plots). The presented results state a high robustness of the decision rule with respect to the investor's risk preference.

As a final parameter, the sensitivity of the investment decision is analyzed for the case of existing gas-fired power plants (**COGAS**, 500 MW) including the value of waiting (see Fig. 11). The existence of those power plants has previously been identified to influence the

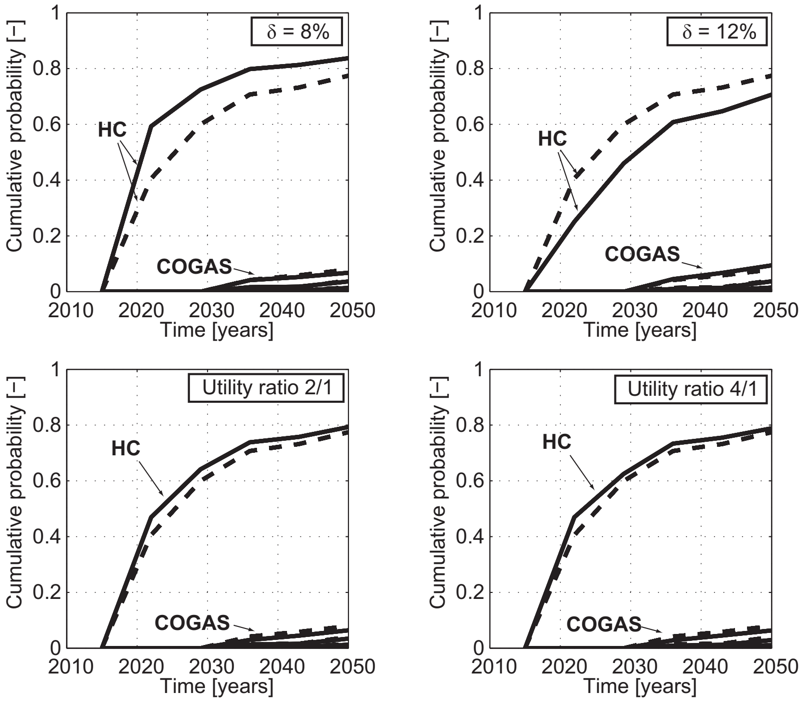

Figure 11: Influence of the investor's risk aversion including the value of waiting on the investment decision of an investor owning a 500 MW gas-fired power plant. The dashed lines depict the solution for the reference case of a risk-neutral investor.

investment decision most (see Fig. 8). Compared to the influence described in the preceeding paragraph, the existing power plant is found to increase the sensitivity of the investment decision on the discount rate. This higher sensitivity on the discount rate is caused by a reduced value of waiting, which itself results from the existing portfolio. However, the sensitivity remains lower compared to the calculations when the value of waiting was ignored. The two lower plots depict the influence of the utility ratio on the investment decision which was found to be of marginal relevance.

4.2 Market conditions for the deployment of CCS

The second part of this section focuses on the market conditions required for a deployment of CCS technologies, e.g., coal- and gas-fired CCS power plants (**HC-IGCC-CCS** and **COGAS-CCS**). Because CCS will most probably serve as a bridging technology between the age of fossil fuel-based electricity generation and the age of renewable energies, it is necessary to identify the required market conditions for an early deployment of CCS. Therefore, the probability of the investment in a base-load CCS power plant for $t = 2022$

is investigated with different values of the initial electricity and carbon dioxide prices. By incorporating other available technologies as well the value of waiting in the decision process enables a realistic estimation of the CCS-technology's potential.

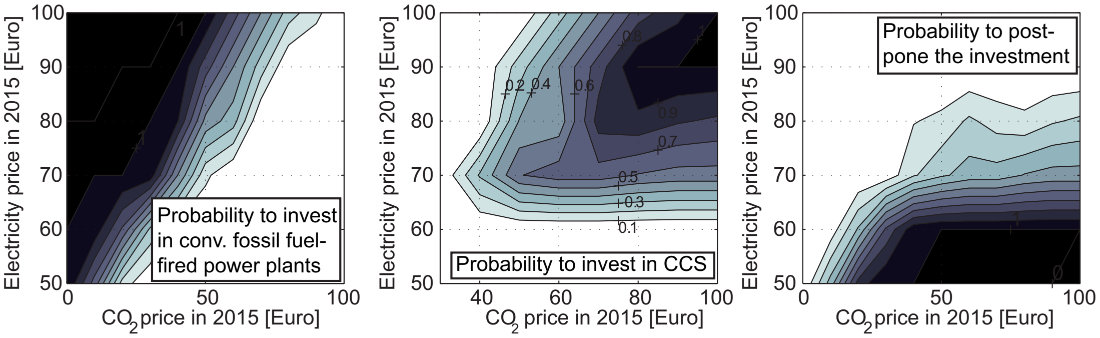

Figure 12: Regime map for the probability to invest in the year 2022 in a specific technology (conventional fossil fuel-fired power plants, left plot; and CCS-technologies, center plot) or to postpone the investment decision (right plot).

In Figure 12, the probability of the investment decision for the year 2022 is shown for a broad variation of the initial electricity and carbon dioxide allowance prices, which has been defined for the year 2015. The investment probability is subdivided into the probability to invest in classical fossil fuel-fired power plants (center plot), in power plants equipped with CCS (left plot) and in the probability to postpone the investment decision (right plot). In the case of a zero carbon dioxide price, the electricity price has to exceed a value of €45 in order to raise the probability to invest to than 50% in a conventional coal-fired power plant in 2022. When comparing these results with today's price of electricity in the long-term market, rather unattractive conditions for the deployment of new fossil fuel-fired power plants are found. For an increasing price of carbon dioxide allowances, the probability to invest in those conventional power plants decreases. In other words, if the price of carbon dioxide allowances rises by 1 Euro, the electricity price would have to increase by approximately .85 Euro in order to maintain the same probability.

For the CCS technologies, the probability to invest starts to rise for a carbon dioxide price above €35. However, for a significant probability of 50%, a carbon price level of 60 €/$\mathrm{t_{CO_2}}$ is required. Still, it is not only the price of carbon dioxide but also the electricity price which has to be above a certain level in order to render investments in CCS profitable. This price of electricity is found to be in the range of 70 €/$\mathrm{MW_h}$, thus being far beyond the actual price level (e.g. EEX electricity spot price ≈ 50 €/MW$_\mathrm{h}$ on average in 2012 and with a negative trend). For the deployment of CCS, electricity prices above 70 €/MW$_\mathrm{h}$ are found to reduce the probability again. This reduction is caused by the opportunity cost of unsold electricity.

5 Conclusion

This paper presents several extensions to our recent multi-dimensional real options model for low-carbon power generation investments (Rohlfs and Madlener, 2011b), enabling the additional consideration of existing power plant portfolios in the decision process for building new power generation units. With the former idea of a technology- and state-dependent risk as well as the capability of the model to account for technological change, the probability of future investments in coal- and gas-fired power plants, and in power plants with and without CCS, has been investigated.

In order to identify the influence of the different model aspects (e.g. the value of waiting, multiple available technologies and an existing power plant portfolio), the investment decision has been evaluated, in a first step, based on a classical NPV decision rule. Using this simple model to evaluate a power plant investment today ($t = 2015$), a strongly negative NPV was found, rendering an investment economically highly unattractive. When tracking the decision into the future, a significant increase in the probability to invest in coal-fired power plants was found (for $t > 2022$). For later times, the probability of coal-fired power plants equipped with CCS was also found to increase. Due to the consideration of base-load power plants whose electricity price is given by the long-time future contracts, the performance of the gas-fired power plants was significantly lower compared to the coal-fired power plants. If an investor has the opportunity to build one of the four types of power plants, the dominance of the hard-coal power plant strongly reduces the probability of investments in the other technologies.

Considering the value of waiting in the decision process resulted in an increase of the expected NPV, although the investment decision was found to be delayed. Noteworthy, the value of waiting resulted also in a strongly modified probability distribution of the NPV. While for the classical NPV decision rule, the probability of the future NPVs is more or less Gaussian-like, the probability for the value of waiting is strongly asymmetric. This asymmetric shape depicts a steep gradient (decreasing probability) if the NPV is smaller than zero and a long tail for positive NPVs. An evaluation of the probability to fall below the desired rate of return, e.g. $\mathrm{NPV} < 0$, yields to a strong reduction if the value of waiting is considered. An important finding is that the value of waiting increases the NPV, while reducing the probability to fall below the desired rate of return. This finding raises the questions of whether the required discount rate has to be narrowed down because of reduced risk.

In the case of existing power plant portfolios, the decision process is influenced when considering the value of waiting. Because the existing power plants vanish the systematic risk of the new project, the resulting volatility diminishes which leads to a reduced value of waiting and thus to a preponement of the investment. Because of the hard coal power plant's dominance, this effect was found to have a strong impact on investors already owning gas-fired power plants. For the case of existing onshore wind parks or coal-fired power plants, the investment decision is only slightly influenced.

In a sensitivity analysis, the decision process was found to be less influenced by the choice of the discount rate and by the risk-averse behavior of the investor if the value of waiting was considered compared to the classical NPV decision rule. It was shown that inclusion of the value of waiting enables a more robust estimation of the probability of future investments. Thus, this model was used in a last step to investigate the market conditions required for a deployment of CCS technology.

In a parametric study, the influence of the carbon dioxide price and the electricity price on the investment decisions was tested in order to find a lower bound of the carbon dioxide price required for the deployment of CCS. For this study, both prices for the initial time considered in the decision process, e.g. $t = 2015$, were varied and the probability to invest in CCS in 2022 was evaluated. It was found that for a significant probability of 50% (i.e. probability to invest in CCS), the carbon dioxide price has to exceed $60\,€/\mathrm{t_{CO_2}}$. In addition, the price of electricity has to be in the range of $70\,€/\mathrm{MW_h}$, being far beyond the actual price levels. However, higher electricity prices reduce the probability of CCS investments again. For the current market situation in 2013 (electricity price of approximately $40\,€/\mathrm{MW_h}$, a high advantage of investment postponement was found, meaning that also in $t = 2022$

the probability of further waiting will be higher than the probability of investments in new power generation units.

References

Abadie, L. M., Chamorro, J. M., Gonzlez-Eguino, M., 2013. Valuing uncertain cash flows from investments that enhance energy efficiency. Journal of Environmental Management 116, 113 – 124.

Bellman, R. E., 1957. Dynamic Programming. Princeton University Press, Princeton, NJ.

Black, F., Scholes, M., 1973. The pricing of options and corporate liabilities. Journal of Political Economy 81, 637 – 654.

CSLF, 2009. Carbon Sequestration Leadership Forum Technology Roadmap: A global response to the challenge of climate change. Carbon Sequestration Leadership Forum, Washington.

Davison, J., 2007. Performance and costs of power plants with capture and storage. Energy 32 (7), 1163 – 1176.

Dixit, A. K., Pindyck, R. S., 1994. Investment under Uncertainty. Princeton University Press, Princeton, NJ.

EPRI, 2011. Post-combustion CO_2 capture technology development. Electric Power Research Institute, Report No. 1022133, Palo Alto, Cal.

European Commission, 2011a. Communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions. A Roadmap for moving to a competitive low carbon economy in 2050. European Commision, Brussels.

European Commission, 2011b. Roadmap for moving to a low-carbon economy in 2050. European Commision, Brussels.

Gamba, A., Trigeorgis, L., 2007. An improved binomial lattice method for multi-dimensional options. Applied Mathematical Finance 14 (5), 453 – 475.

Hammond, G., Akwe, S. O., Williams, S., 2011. Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. Energy 36 (2), 975 – 984.

Hull, J. C., 2005. Options, Futures and Other Derivatives. Pearson, Prentice Hall, New Jersey.

IEA, 2010. Energy Technology Perspectives 2010: Scenarios and Strategies to 2050: Complete Edition. Vol. 2008. OECD—Organisation for Economic Co-operation and Development / International Energy Agency, Paris.

IEA, 2011. Cost and Performance of Carbon Dioxide Capture from Power Generation. OECD—Organisation for Economic Co-operation and Development, International Energy Agency, Paris.

Markowitz, H. M., 1952. Portfolio selection. Journal of Finance 7, 77 – 91.

Markowitz, H. M., 1991. Foundations of portfolio theory. The Journal of Finance 46 (2), 469–477.

McCoy, S. T., 2008. The economics of CO_2 transport by pipeline and storage in saline aquifers and oil reservoirs. Ph.D. thesis, Carnegie Mellon University, Pittsburgh, PA.

McDonald, R., Siegel, D., November 1986. The value of waiting to invest. The Quarterly Journal of Economics 101 (4), 707 – 727.

Nitsch, J., Pregger, T., Scholz, Y., Naegler, T., Sterner, M., Gerhardt, N., von Oehsen, A., Carsten, P., Saint-Drenan, Y.-M., Wenzel, B., 2010. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global - Leitstudie 2010. Bundesumweltministerium BMU - FKZ 03MAP146.

Pehnt, M., Henkel, J., 2009. Life cycle assessment of carbon dioxide capture and storage from lignite power plants. International Journal of Greenhouse Gas Control 3 (1), 49 – 66.

Reinelt, P., Keith, D., 2007. Carbon capture retrofits and the cost of regulatory uncertainty. The Energy Journal 28 (4), 101 – 127.

Rohlfs, W., Madlener, R., 2011a. Multi-commodity real options analysis of power plant investments: Discounting endogenous risk structures, FCN Working Paper No. 22/2011, Institute for Future Energy Consumer Needs and Behavior (FCN), RWTH Aachen University, Aachen, Germany, December.

Rohlfs, W., Madlener, R., 2011b. Valuation of CCS-ready coal-fired power plants: a multi-dimensional real options approach. Energy Systems 2 (3-4), 243 – 261.

Rohlfs, W., Madlener, R., 2013a. Assessment of clean-coal strategies: The questionable merits of carbon capture-readiness. Energy 52, 27 – 36.

Rohlfs, W., Madlener, R., 2013b. Investment Decisions Under Uncertainty: CCS Competing with Green Energy Technologies. Energy Procedia 37 (0), 7029 – 7038.

Rubin, E. S., 2012. Understanding the pitfalls of CCS cost estimates. International Journal of Greenhouse Gas Control 10, 181–190.

Rubin, E. S., Mantripragada, H., Marks, A., Versteeg, P., Kitchin, J., 2012. The outlook for improved carbon capture technology. Progress in Energy and Combustion Science 38 (5), 630 – 671.

Rubinstein, M., 1994. Return to Oz. Risk 7 (11), 67 – 71.

US Department of Energy, 2010. Carbon sequestration technology roadmap and program plan. Pittsburgh: National Energy Technology Laboratory.

World Energy Council, 2007. Deciding the Future: Energy Policy Scenarios to 2050. World Energy Council, London.

Zapp, P., Schreiber, A., Marx, J., Haines, M., Hake, J.-F., Gale, J., 2012. Overall environmental impacts of ccs technologiesa life cycle approach. International Journal of Greenhouse Gas Control 8, 12 – 21.

List of FCN Working Papers

2013

Grieser B., Madlener R., Sunak Y. (2013). Economics of Small Wind Power Plants in Urban Settings: An Empirical Investigation for Germany, FCN Working Paper No. 1/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

Madlener R., Specht J.M. (2013). An Exploratory Economic Analysis of Underground Pumped-Storage Hydro Power Plants in Abandoned Coal Mines, FCN Working Paper No. 2/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Kroniger D., Madlener R. (2013). Hydrogen Storage for Wind Parks: A Real Options Evaluation for an Optimal Investment in More Flexibility, FCN Working Paper No. 3/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Petersen C., Madlener R. (2013). The Impact of Distributed Generation from Renewables on the Valuation and Marketing of Coal-Fired and IGCC Power Plants, FCN Working Paper No. 4/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Oberst C.A., Oelgemöller J. (2013). Economic Growth and Regional Labor Market Development in German Regions: Okun’s Law in a Spatial Context, FCN Working Paper No. 5/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Harmsen - van Hout M.J.W., Ghosh G.S., Madlener R. (2013). An Evaluation of Attribute Anchoring Bias in a Choice Experimental Setting. FCN Working Paper No. 6/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Harmsen - van Hout M.J.W., Ghosh G.S., Madlener R. (2013). The Impact of Green Framing on Consumers’ Valuations of Energy-Saving Measures. FCN Working Paper No. 7/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Rosen C., Madlener R. (2013). An Experimental Analysis of Single vs. Multiple Bids in Auctions of Divisible Goods, FCN Working Paper No. 8/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Palmer J., Sorda G., Madlener R. (2013). Modeling the Diffusion of Residential Photovoltaic Systems in Italy: An Agent-based Simulation, FCN Working Paper No. 9/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Bruns S.B., Gross C. (2013). What if Energy Time Series are not Independent? Implications for Energy-GDP Causality Analysis, FCN Working Paper No. 10/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Bruns S.B., Gross C., Stern D.I. (2013). Is There Really Granger Causality Between Energy Use and Output?, FCN Working Paper No. 11/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Rohlfs W., Madlener R. (2013). Optimal Power Generation Investment: Impact of Technology Choices and Existing Portfolios for Deploying Low-Carbon Coal Technologies, FCN Working Paper No. 12/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

2012

Ghosh G., Shortle J. (2012). Managing Pollution Risk through Emissions Trading, FCN Working Paper No. 1/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

Palzer A., Westner G., Madlener M. (2012). Evaluation of Different Hedging Strategies for Commodity Price Risks of Industrial Cogeneration Plants, FCN Working Paper No. 2/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March (revised March 2013).

Sunak Y., Madlener R. (2012). The Impact of Wind Farms on Property Values: A Geographically Weighted Hedonic Pricing Model, FCN Working Paper No. 3/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May (revised March 2013).

Achtnicht M., Madlener R. (2012). Factors Influencing German House Owners' Preferences on Energy Retrofits, FCN Working Paper No. 4/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Schabram J., Madlener R. (2012). The German Market Premium for Renewable Electricity: Profitability and Risk of Self-Marketing, FCN Working Paper No. 5/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Garbuzova M., Madlener R. (2012). Russia’s Emerging ESCO Market: Prospects and Barriers for Energy Efficiency Investments, FCN Working Paper No. 6/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July (revised December 2012).

Rosen C., Madlener R. (2012). Auction Design for Local Reserve Energy Markets, FCN Working Paper No. 7/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July (revised March 2013).

Sorda G., Madlener R. (2012). Cost-Effectiveness of Lignocellulose Biorefineries and their Impact on the Deciduous Wood Markets in Germany. FCN Working Paper No. 8/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Madlener R., Ortlieb C. (2012). An Investigation of the Economic Viability of Wave Energy Technology: The Case of the Ocean Harvester, FCN Working Paper No. 9/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

Hampe J., Madlener R. (2012). Economics of High-Temperature Nuclear Reactors for Industrial Cogeneration, FCN Working Paper No. 10/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

Knaut A., Madlener R., Rosen C., Vogt C. (2012). Impact of Temperature Uncertainty on the Economic Valuation of Geothermal Projects: A Real Options Approach, FCN Working Paper No. 11/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Hünteler J., Niebuhr C.F., Schmidt T.S., Madlener R., Hoffmann V.H. (2012). Financing Feed-in Tariffs in Developing Countries under a Post-Kyoto Climate Policy Regime: A Case Study of Thailand, FCN Working Paper No. 12/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Blass N., Madlener R. (2012). Structural Inefficiencies and Benchmarking of Water Supply Companies in Germany, FCN Working Paper No. 13/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Madlener R., Schabram J. (2012). Predicting Reserve Energy from New Renewables by Means of Principal Component Analysis and Copula Functions, FCN Working Paper No. 14/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Harzendorf F., Madlener R. (2012). Optimal Investment in Gas-Fired Engine-CHP Plants in Germany: A Real Options Approach, FCN Working Paper No. 15/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Schmitz M., Madlener R. (2012). Economic Feasibility of Kite-Based Wind Energy Powerships with CAES or Hydrogen Storage, FCN Working Paper No. 16/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Dergiades T., Christofidou G., Madlener R. (2012). The Nexus between Natural Gas Spot and Futures Prices at NYMEX: What about Non-Linear Causality?, FCN Working Paper No. 17/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Rohlfs W., Madlener R. (2012). Assessment of Clean-Coal Strategies: The Questionable Merits of Carbon Capture-Readiness, FCN Working Paper No. 18/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Wüstemeyer C., Bunn D., Madlener R. (2012). Bridging the Gap between Onshore and Offshore Innovations by the European Wind Power Supply Industry: A Survey-based Analysis, FCN Working Paper No. 19/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Fuhrmann J., Madlener R. (2012). Evaluation of Synergies in the Context of European Multi-Business Utilities, FCN Working Paper No. 20/2012, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

2011

Sorda G., Sunak Y., Madlener R. (2011). A Spatial MAS Simulation to Evaluate the Promotion of Electricity from Agricultural Biogas Plants in Germany, FCN Working Paper No. 1/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January (revised October 2012).

Madlener R., Hauertmann M. (2011). Rebound Effects in German Residential Heating: Do Ownership and Income Matter?, FCN Working Paper No. 2/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Garbuzova M., Madlener R. (2011). Towards an Efficient and Low-Carbon Economy Post-2012: Opportunities and Barriers for Foreign Companies in the Russian Market, FCN Working Paper No. 3/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February (revised July 2011).

Westner G., Madlener R. (2011). The Impact of Modified EU ETS Allocation Principles on the Economics of CHP-Based District Heating Networks. FCN Working Paper No. 4/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Madlener R., Ruschhaupt J. (2011). Modeling the Influence of Network Externalities and Quality on Market Shares of Plug-in Hybrid Vehicles, FCN Working Paper No. 5/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Juckenack S., Madlener R. (2011). Optimal Time to Start Serial Production: The Case of the Direct Drive Wind Turbine of Siemens Wind Power A/S, FCN Working Paper No. 6/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Madlener R., Sicking S. (2011). Assessing the Economic Potential of Microdrilling in Geothermal Exploration, FCN Working Paper No. 7/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Bernstein R., Madlener R. (2011). Responsiveness of Residential Electricity Demand in OECD Countries: A Panel Cointegration and Causality Analysis, FCN Working Paper No. 8/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April.

Michelsen C.C., Madlener R. (2011). Homeowners' Preferences for Adopting Residential Heating Systems: A Discrete Choice Analysis for Germany, FCN Working Paper No. 9/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May (revised January 2012).

Madlener R., Glensk B., Weber V. (2011). Fuzzy Portfolio Optimization of Onshore Wind Power Plants. FCN Working Paper No. 10/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Glensk B., Madlener R. (2011). Portfolio Selection Methods and their Empirical Applicability to Real Assets in Energy Markets. FCN Working Paper No. 11/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Kraas B., Schroedter-Homscheidt M., Pulvermüller B., Madlener R. (2011). Economic Assessment of a Concentrating Solar Power Forecasting System for Participation in the Spanish Electricity Market, FCN Working Paper No. 12/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Stocker A., Großmann A., Madlener R., Wolter M.I., (2011). Sustainable Energy Development in Austria Until 2020: Insights from Applying the Integrated Model “e3.at”, FCN Working Paper No. 13/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Kumbaroğlu G., Madlener R. (2011). Evaluation of Economically Optimal Retrofit Investment Options for Energy Savings in Buildings. FCN Working Paper No. 14/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Bernstein R., Madlener R. (2011). Residential Natural Gas Demand Elasticities in OECD Countries: An ARDL Bounds Testing Approach, FCN Working Paper No. 15/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

Glensk B., Madlener R. (2011). Dynamic Portfolio Selection Methods for Power Generation Assets, FCN Working Paper No. 16/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Michelsen C.C., Madlener R. (2011). Homeowners' Motivation to Adopt a Residential Heating System: A Principal Component Analysis, FCN Working Paper No. 17/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised January 2013).

Razlaf J., Madlener R. (2011). Performance Measurement of CCS Power Plants Using the Capital Asset Pricing Model, FCN Working Paper No. 18/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Himpler S., Madlener R. (2011). Repowering of Wind Turbines: Economics and Optimal Timing, FCN Working Paper No. 19/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised July 2012).

Hackbarth A., Madlener R. (2011). Consumer Preferences for Alternative Fuel Vehicles: A Discrete Choice Analysis, FCN Working Paper No. 20/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December (revised December 2012).

Heuser B., Madlener R. (2011). Geothermal Heat and Power Generation with Binary Plants: A Two-Factor Real Options Analysis, FCN Working Paper No. 21/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Rohlfs W., Madlener R. (2011). Multi-Commodity Real Options Analysis of Power Plant Investments: Discounting Endogenous Risk Structures, FCN Working Paper No. 22/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December (revised July 2012).

2010

Lang J., Madlener R. (2010). Relevance of Risk Capital and Margining for the Valuation of Power Plants: Cash Requirements for Credit Risk Mitigation, FCN Working Paper No. 1/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Michelsen C.C., Madlener R. (2010). Integrated Theoretical Framework for a Homeowner’s Decision in Favor of an Innovative Residential Heating System, FCN Working Paper No. 2/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Harmsen - van Hout M.J.W., Herings P.J.-J., Dellaert B.G.C. (2010). The Structure of Online Consumer Communication Networks, FCN Working Paper No. 3/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Madlener R., Neustadt I. (2010). Renewable Energy Policy in the Presence of Innovation: Does Government Pre-Commitment Matter?, FCN Working Paper No. 4/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April (revised June 2010 and December 2011).

Harmsen - van Hout M.J.W., Dellaert B.G.C., Herings, P.J.-J. (2010). Behavioral Effects in Individual Decisions of Network Formation: Complexity Reduces Payoff Orientation and Social Preferences, FCN Working Paper No. 5/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Lohwasser R., Madlener R. (2010). Relating R&D and Investment Policies to CCS Market Diffusion Through Two-Factor Learning, FCN Working Paper No. 6/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Rohlfs W., Madlener R. (2010). Valuation of CCS-Ready Coal-Fired Power Plants: A Multi-Dimensional Real Options Approach, FCN Working Paper No. 7/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Rohlfs W., Madlener R. (2010). Cost Effectiveness of Carbon Capture-Ready Coal Power Plants with Delayed Retrofit, FCN Working Paper No. 8/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August (revised December 2010).

Gampert M., Madlener R. (2010). Pan-European Management of Electricity Portfolios: Risks and Opportunities of Contract Bundling, FCN Working Paper No. 9/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Glensk B., Madlener R. (2010). Fuzzy Portfolio Optimization for Power Generation Assets, FCN Working Paper No. 10/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Lang J., Madlener R. (2010). Portfolio Optimization for Power Plants: The Impact of Credit Risk Mitigation and Margining, FCN Working Paper No. 11/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Westner G., Madlener R. (2010). Investment in New Power Generation Under Uncertainty: Benefits of CHP vs. Condensing Plants in a Copula-Based Analysis, FCN Working Paper No. 12/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Bellmann E., Lang J., Madlener R. (2010). Cost Evaluation of Credit Risk Securitization in the Electricity Industry: Credit Default Acceptance vs. Margining Costs, FCN Working Paper No. 13/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September (revised May 2011).

Ernst C.-S., Lunz B., Hackbarth A., Madlener R., Sauer D.-U., Eckstein L. (2010). Optimal Battery Size for Serial Plug-in Hybrid Vehicles: A Model-Based Economic Analysis for Germany, FCN Working Paper No. 14/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October (revised June 2011).

Harmsen - van Hout M.J.W., Herings P.J.-J., Dellaert B.G.C. (2010). Communication Network Formation with Link Specificity and Value Transferability, FCN Working Paper No. 15/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Paulun T., Feess E., Madlener R. (2010). Why Higher Price Sensitivity of Consumers May Increase Average Prices: An Analysis of the European Electricity Market, FCN Working Paper No. 16/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Glensk B. (2010). Portfolio Impact of New Power Generation Investments of E.ON in Germany, Sweden and the UK, FCN Working Paper No. 17/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Kwasnica A., Shortle J. (2010). A Laboratory Experiment to Compare Two Market Institutions for Emissions Trading, FCN Working Paper No. 18/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Bernstein R., Madlener R. (2010). Short- and Long-Run Electricity Demand Elasticities at the Subsectoral Level: A Cointegration Analysis for German Manufacturing Industries, FCN Working Paper No. 19/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Mazur C., Madlener R. (2010). Impact of Plug-in Hybrid Electric Vehicles and Charging Regimes on Power Generation Costs and Emissions in Germany, FCN Working Paper No. 20/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Stoverink S. (2010). Power Plant Investments in the Turkish Electricity Sector: A Real Options Approach Taking into Account Market Liberalization, FCN Working Paper No. 21/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December (revised July 2011).

Melchior T., Madlener R. (2010). Economic Evaluation of IGCC Plants with Hot Gas Cleaning, FCN Working Paper No. 22/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Lüschen A., Madlener R. (2010). Economics of Biomass Co-Firing in New Hard Coal Power Plants in Germany, FCN Working Paper No. 23/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December (revised July 2012).

Madlener R., Tomm V. (2010). Electricity Consumption of an Ageing Society: Empirical Evidence from a Swiss Household Survey, FCN Working Paper No. 24/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Tomm V., Madlener R. (2010). Appliance Endowment and User Behaviour by Age Group: Insights from a Swiss Micro-Survey on Residential Electricity Demand, FCN Working Paper No. 25/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Hinrichs H., Madlener R., Pearson P. (2010). Liberalisation of Germany's Electricity System and the Ways Forward of the Unbundling Process: A Historical Perspective and an Outlook, FCN Working Paper No. 26/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Achtnicht M. (2010). Do Environmental Benefits Matter? A Choice Experiment Among House Owners in Germany, FCN Working Paper No. 27/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

2009

Madlener R., Mathar T. (2009). Development Trends and Economics of Concentrating Solar Power Generation Technologies: A Comparative Analysis, FCN Working Paper No. 1/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Latz J. (2009). Centralized and Integrated Decentralized Compressed Air Energy Storage for Enhanced Grid Integration of Wind Power, FCN Working Paper No. 2/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised September 2010).

Kraemer C., Madlener R. (2009). Using Fuzzy Real Options Valuation for Assessing Investments in NGCC and CCS Energy Conversion Technology, FCN Working Paper No. 3/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Westner G., Madlener R. (2009). Development of Cogeneration in Germany: A Dynamic Portfolio Analysis Based on the New Regulatory Framework, FCN Working Paper No. 4/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised March 2010).

Westner G., Madlener R. (2009). The Benefit of Regional Diversification of Cogeneration Investments in Europe: A Mean-Variance Portfolio Analysis, FCN Working Paper No. 5/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised March 2010).

Lohwasser R., Madlener R. (2009). Simulation of the European Electricity Market and CCS Development with the HECTOR Model, FCN Working Paper No. 6/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Lohwasser R., Madlener R. (2009). Impact of CCS on the Economics of Coal-Fired Power Plants – Why Investment Costs Do and Efficiency Doesn't Matter, FCN Working Paper No. 7/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Holtermann T., Madlener R. (2009). Assessment of the Technological Development and Economic Potential of Photobioreactors, FCN Working Paper No. 8/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Carriazo F. (2009). A Comparison of Three Methods of Estimation in the Context of Spatial Modeling, FCN Working Paper No. 9/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Shortle J. (2009). Water Quality Trading when Nonpoint Pollution Loads are Stochastic, FCN Working Paper No. 10/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Ribaudo M., Shortle J. (2009). Do Baseline Requirements hinder Trades in Water Quality Trading Programs?, FCN Working Paper No. 11/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Glensk B., Raymond P. (2009). Investigation of E.ON's Power Generation Assets by Using Mean-Variance Portfolio Analysis, FCN Working Paper No. 12/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

2008

Madlener R., Gao W., Neustadt I., Zweifel P. (2008). Promoting Renewable Electricity Generation in Imperfect Markets: Price vs. Quantity Policies, FCN Working Paper No. 1/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July (revised May 2009).

Madlener R., Wenk C. (2008). Efficient Investment Portfolios for the Swiss Electricity Supply Sector, FCN Working Paper No. 2/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Omann I., Kowalski K., Bohunovsky L., Madlener R., Stagl S. (2008). The Influence of Social Preferences on Multi-Criteria Evaluation of Energy Scenarios, FCN Working Paper No. 3/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Bernstein R., Madlener R. (2008). The Impact of Disaggregated ICT Capital on Electricity Intensity of Production: Econometric Analysis of Major European Industries, FCN Working Paper No. 4/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Erber G., Madlener R. (2008). Impact of ICT and Human Skills on the European Financial Intermediation Sector, FCN Working Paper No. 5/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

FCN Working Papers are free of charge. They can mostly be downloaded in pdf format from the FCN / E.ON ERC Website (www.eonerc.rwth-aachen.de/fcn) and the SSRN Website (www.ssrn.com), respectively. Alternatively, they may also be ordered as hardcopies from Ms Sabine Schill (Phone: +49 (0) 241-80 49820, E-mail: post_fcn@eonerc.rwth-aachen.de), RWTH Aachen University, Institute for Future Energy Consumer Needs and Behavior (FCN), Chair of Energy Economics and Management (Prof. Dr. Reinhard Madlener), Mathieustrasse 10, 52074 Aachen, Germany.