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Investment decisions under uncertainty: CCS competing with green energy technologies

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Abstract

Investors in the electricity supply industry are spoilt for choice when considering capital-intensive investments in alternative power plants. Although such kind of decision-making problems can already be very complicated due to multiple financial risks, complexity rises further if there is the possibility that the investment can be postponed. This flexibility causes a so-called ‘value of waiting’ which is forfeited as soon as the investment is made (the “real option” is exercised). In our study with representative data for Europe / Germany, we use such a model in order to find the optimal investment decision in a situation where the electric utility has the choice between an IGCC power plant (with and without CCS), a combined gas and steam power plant with CCS, and an offshore wind farm. We compare the option value for the case that each technology is available individually, or in combination with other technologies. Finally, we consider the influence of subsidies for renewables, which can strongly promote the diffusion of renewable energy technologies and, therefore, reduce the value of CCS power plants.

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1. Introduction

Over the last two decades, electricity markets have seen strong changes concerning regulatory policy as well as technical improvements. Driven by the awareness of global warming, mainly caused by the carbon dioxide emissions from fossil-fuel combustion, and the increasing demand of energy, we globally face the need of renewing our energy conversion technologies. One possibility is the application of carbon capture and storage (CCS) technology to fossil-fuel-fired power plants, reducing the carbon dioxide emissions to the atmosphere. Another alternative are green technologies using renewable energy sources, such as solar radiation, wind or water power. However, as fossil fuels are finite, they must be completely replaced by renewable energy technologies in the distant future. Nevertheless, CCS may play a major role as a bridging technology, covering the high demand of electricity in the near future while waiting for further improvements in renewable and energy storage technologies.

From an economic point of view, the potential of CCS as a bridging technology is limited by the competition of CCS with conventional power plants today and with the competition of CCS with renewable energy sources in the future. For the German market, a broad study “RECCS plus: Comparison of Renewable Energy Technologies with Carbon Dioxide Capture and Storage (CCS)” [1] (see also Viebahn [2,3]) was conducted by the Wuppertal Institute for Climate, Environment and Energy. This study found that the electricity-generating costs for fossil-fuel-fired power plants with and without CCS will be more expensive than the ones of renewable energies in Germany even in the short to medium term. Only under the assumption that CCS is already commercially available in 2020, a small window for this technology can be found in the German energy mix.

The motivation for this study is threefold. First, we want to additionally account for the value of waiting in the decision process. Including the option to wait might cause investors to delay their investment decision in favor to renewable energies, further decreasing the potential of CCS. Second, we want to account for technology-dependent risk, which is driven by the technology-specific combination of input and output quantities, such as for instance electricity, fuel, and CO₂ certificates. Last but not least, we aim at directly comparing different power plants, allowing the investor in his decision process to choose between various available technologies, such as offshore wind, conventional hard-coal, and CCS power plants fired with hard coal or natural gas.

The remainder of this paper is organized as follows: In section 2 the real options model with the segregated discounting is described. Section 3 summarizes the economical and technological data used for the later model application. Section 4 presents the results from applying the model for various carbon dioxide price scenarios. Section 5 concludes and suggests some political implications.

2. Model

In order to evaluate the potential of CCS for becoming a bridging technology, a new multi-dimensional real options model with endogenous risk treatment, as introduced in Rohlfs and Madlener [4], has been used. The model allows to choose between various technologies available and for the option to postpone the investment (the “option to wait”, see McDonald and Siegel [5]) in order to maximize the investor’s financial value.

In principle, the economic value of all technologies considered can be calculated based on the specific cost of investment, operation and maintenance cost, and technology-specific parameters, such as the specific electricity production, fuel consumption, CO₂ emissions, average utilization, and lifetime. The incoming and outgoing cash flows during the power plant’s lifetime are coupled to the price of a few basic underlyings (e.g. price of electricity, fuel, and CO₂), which are modeled as stochastic processes and introduce the multi-dimensionality of the proposed problem. Due to the different growth rates, volatilities,
and correlations between the prices, the economic risk associated with each power plant is endogenously given by the technology-specific combination of these underlyings. This fact prohibits predefined discount rates, which cannot account for the technology-specific risk and thus calls for an endogenous risk treatment.

The main part of this model (see Fig. 1) is a multi-dimensional real options approach, for which the lattice method (for the one-dimensional case introduced by Cox, Ross, and Rubinstein [6]) has been used, allowing for a more realistic modeling compared to the case where only one decisive variable is treated as stochastic. Beginning with a deterministic initial price, a multi-dimensional tree is constructed up to the point in time when the option is assumed to expire (we use the date 2050). Working backwards the decision tree, which consists of the opportunity to invest in one of the different power plants or to delay the investment decision by one period, the real option value is evaluated. The decision depends on the exercising value and the value of waiting. For the exercising value (NPV) at each node of the tree, we apply the Monte Carlo Simulation technique, which allows the required risk treatment, e.g. concerning
discounting. This calculation procedure finally leads to the option value (W) at the beginning of the decision tree.

2.1. Time- and risk-adjusted cash-flow evaluation

In this model, we apply a novel method of endogenous risk treatment with segregated risk- and time discounting. The present approach is motivated by the following two principles: First, due to the fixed ratio between input and output quantities of the power plant and the long lifetime, the influence of the different cash flows (income for electricity output, expenses for fuel and CO₂ permits) changes over the years. This affects the uncertainty of the net cash flow and, therefore, also the risk of the project. In finance theory, especially in portfolio optimization theory, an investor is able to adjust his portfolio continuously by way of trading, which allows retaining a constant ratio between different stocks. However, if such a continuous adjustment is not possible for an investor, the risk-discounting must account for a time-dependent volatility. The second point concerns another major difference between investments in financial assets and in real assets such as power plants. For the latter, the continuous output of electricity, input of fuel, and requirement of CO₂ emission permits would be equivalent to a continuous selling or buying of stocks. However, in finance theory, it is mostly assumed that the stocks are kept and their accretion is realized. The continuous in- and output requires that present values (PV) of cash flows gained at various times have to be added up. Due to a strong correlation between prices of subsequent time steps, a simple addition of those PVs is inaccurate. In order to include both mentioned principles into the model, a segregated time- and risk-discounting method is applied. For this, an additional stochastic process, representing a benchmark asset, has been introduced. This benchmark price is used to calculate the present value of all cash flows. In order to consider the influence of risk, multiple exercising values are determined by a Monte Carlo simulation of the underlying assets. A mean, risk-adjusted exercising utility value is estimated by weighting all exercising values according to a quadratic utility function.

2.2. Modeling the subsidies of renewable energy sources

In many countries, such as for instance in Germany and France, subsidies are introduced in order to promote renewable energy sources. Those subsidies generally ensure a predefined deterministic payment for the electricity fed into the grid, the costs of which are typically borne via a levy by the final electricity
consumers. In our study, we focus on subsidies for onshore and offshore wind parks, as those technologies are potentially able to contribute significantly to the electricity generation in northern Europe. The current legislation in Germany, for example, promises subsidies for a time period of 20 years. This time period even exceeds the assumed lifetime of wind power plants in our study (18 versus 20 years), which we adopted from the German “Pilot Study 2010” (“Leitstudie 2010”; Nitsch et al. [7]). Although a one-to-one implementation of the complex and country-dependent legislation is not possible in our model, the two main influences on the risk structure of the investment decision shall be accounted for. First, the subsidies guarantee the mandatory minimum payment for the electricity generated if the power plant starts operating before or in 2020. Second, the subsidies are subject to degression (i.e. the feed-in tariffs granted decrease over time in line with cost reductions achieved), causing a low or even negative value of waiting. Figure 2 illustrates schematically the risk pattern of the electricity price as well as for the NPV gained. Starting in 2015, the initial electricity price is known. For the case of no subsidies, a stochastically distributed NPV results, caused by the uncertain cash flows during the power plant’s lifetime. If high subsidies exist, economic uncertainty is reduced, leading to an almost deterministic NPV. Over time, the range of electricity prices increases, while the subsidies constantly decrease. This might cause electricity prices in the market to overcome the guaranteed payment of the subsidies. For this case, we assume that the power plant operator sells the electricity directly to the market, which results in an increase in uncertainty. However, subsidies still act as a lower barrier, protecting the investor from high losses. After 2020, when subsidies completely stop, uncertainty increases strongly.

3. Data and scenario definition

The following section briefly summarizes the economic and technical boundary conditions assumed in this study. For further information, we refer to Rohlfs and Madlener [4].

The price projections (growth rate and volatility) for electricity, coal, natural gas and carbon permits were calculated based on the predictions of the prices assumed in the German Pilot Study 2010 [7]. The correlation coefficients are estimated based on historical price data provided by the European Energy Exchange (EEX) for electricity, coal, and natural gas as well as the EU ETS emission allowances. Table 1 summarizes the economic data used in this study.

The technological data used are also taken from the German “Pilot Study 2010”, which provides projections for the required specifications until 2050 (see Table 2). In order to allow for a comparison of the different technologies, we base our analysis on the investment in a power plant with an electricity generation capacity of 500 MWel. Fuel consumption (if any) is calculated by the given net efficiency and the specific energy contents of the fuel. The cost for transporting and storing CO₂ is assumed to be 4 €/tCO₂ (in line with McCoy [8]).

Table 1. Economic data used in this study

| Parameter | \( P_{el} \) [€] | \( \alpha_e \) | \( \sigma_e \) | \( \rho_{el} \) | \( \rho_{coal} \) | \( \rho_{gas} \) | \( \rho_{CO2} \) | \( \rho_{M} \) |
|-----------|-----------------|-----------------|-----------------|-------------|-------------|-------------|-------------|-------------|
| \( P_{el} \) | 60 | 4.00% | 4.00% | 1.000 | 0.608 | 0.702 | 0.518 | 0.140 |
| \( P_{coal} \) | 69 | 4.18% | 7.09% | 0.608 | 1.000 | 0.603 | 0.250 | 0.260 |
| \( P_{gas} \) | 5.5 | 4.03% | 6.70% | 0.702 | 0.603 | 1.000 | 0.273 | 0.150 |
| \( P_{CO2} \) | 20 | 4.14% | 7.07% | 0.518 | 0.250 | 0.273 | 1.000 | 0.201 |
| \( P_{M} \) | 1 | 2.00% | 2.00% | 0.140 | 0.260 | 0.150 | 0.201 | 1.000 |
Table 2. Characterizations of the three power plants technologies investigated in this study

| Name, abbr., O&M cost, lifetime | Unit | Year | 2015 | 2020 | 2030 | 2040 | 2050 |
|--------------------------------|------|------|------|------|------|------|------|
| Offshore wind, OFFW, 5.5% Investment/a, 18 a | av. utilization, h/a | 2015 | 3500 | 3700 | 3800 | 3850 | 3900 |
| Hard coal integrated gasification combined cycle with CCS, HC-IGCC-CCS, 2% Investment /a, 25 a | efficiency | 2020 | 52 | 54 | 54 | 54 | 54 |
| | av. utilization, h/a | 2030 | 5000 | 5000 | 5000 | 5000 | 5000 |
| | spec. invest. cost, €/kW | 2040 | - | 2200 | 2200 | 2200 | 2200 |
| | kg CO₂/MWh | 2050 | - | 107 | 102 | 102 | 102 |
| Combined gas and steam with CCS, COGAS-CCS, 2% Investment /a, 25 a | efficiency | 2015 | 50 | 52 | 52 | 52 | 52 |
| | av. utilization, h/a | 2020 | - | 5000 | 5000 | 5000 | 5000 |
| | spec. invest. cost, €/kW | 2030 | - | 1100 | 1100 | 1100 | 1100 |
| | kg CO₂/MWh | 2040 | 59 | 57 | 57 | 57 | 57 |

4. Results

The results presented in this section are divided into two parts. First, in section 4.1, the effect of green energy technologies and conventional coal- and gas-fired power plants on investment decisions in CCS is investigated. In section 4.2, the influence of subsidies for green energy technologies is analyzed in detail.

4.1. The potential of CCS as bridging technology

In order to evaluate the potential of CCS power plants (hard coal-fired integrated gasification combined cycle, HC-IGCC-CCS, and gas-fired combined gas and steam, COGAS-CCS, we determine the option value for various decision processes. As a first reference, both power plants are treated separately, allowing only for the decision “invest”, “wait”, and “expire”, respectively.

In Fig. 3, the upper two plots depict the decision process in the eight time steps considered. The bars illustrate the distribution of the decisions made at the specific time step resulting from the various states of the world accounted for. Practically, the bars are determined by the sum of the probabilities of each investment decision at each node of the time step considered. For the HC-IGCC-CCS power plant, for instance, we find a probability to end in a state of the world that is preferable to invest for \( t = 2050 \) of about 78 percent. While the last node only allows the option to expire (“no investment”) if the state of the world is not supporting a profitable investment, the preceding nodes may suggest to wait. The second information given in those plots is the cumulative probability of an investment in the specific power plant. Due to the fact that positive investment decisions in preceding time steps preclude an investment at a later time (only one investment is possible), only nodes which follow a decision path of “waiting” may result in an investment. Therefore, the cumulative probability can provide some insights regarding the overall probability of having invested in the specific power plant. This probability is estimated by a second Monte Carlo simulation that is based on the previously identified decision tree. Note that although the instantaneous probability increases only slightly over time for the HC-IGCC-CCS power plant, a stronger increase in the cumulative probability is found. At first sight, this behavior seems absurd. Why should the cumulative probability rise while the instantaneous one does not? An explanation for this behavior can be found in the multi-dimensionality of the problem. The threshold value, which constitutes the border between the regimes of “investing” and “waiting”, defines a complex surface in this multi-dimensional
Fig. 3. Influence of green energy (wind offshore) on investment decisions in CCS technologies

space. Therefore, the various price paths can penetrate the region of “investing” from multiple directions. If the regime of “waiting” is largely increased in one dimension (e.g. due to an increase in the CO2 permit price), a penetration into the regime of “investing” by price paths can still occur from other directions (e.g. due to reducing fuel or increasing electricity prices), thus increasing the cumulative probability to invest.

The plots of the second to the fourth row illustrate the influence of other competing technologies (offshore wind - OFFW, hard coal - HC, and hard coal IGCC - HC-IGCC), on the probability to invest in CCS technologies. Thereby, the displacement of the CCS technologies by the offshore wind park is seen to increase over time, reaching a displacement of more than 70 percent in 2050. A similarly strong displacement is also seen due to the conventional HC and the HC-IGCC power plant.

The plot on the right hand side illustrates the investment decision for the case that all available technologies compete with each other. The results show a low probability for both CCS technologies. In the first years, a strong displacement by the conventional hard coal- and gas-fired power plants exists. Later, the investment decision is in favor of the offshore wind power plants.
4.2. The influence of subsidies for renewable energy sources

A special focus of this study is the influence of renewable energy sources and related subsidies on investments in CCS power plants. Figure 4 summarizes the results for the three different initial CO₂ price levels considered as well as for the case of subsidies and no subsidies. Technologies under consideration are: HC-IGCC-CCS, COGAS-CCS, and OFFW. Additionally to the plotted instantaneous and cumulative probability distribution, the option value, \( W \), is given in the left upper corner of each plot.

In the absence of subsidies, we find for the low CO₂ price scenario \( (P_{\text{CO}_2} = \€5) \) a high value of waiting. The probability of investments in CCS technologies rises from 2025 onwards, but does not exceed a value of 20 percent in 2050. For OFFW, the value of waiting is much larger due to the steeper learning curve, wherefore a first increase in probability is found as late as in 2040. However, the probability of an investment rises significantly and reaches a value of 60 percent in 2050. Note that the probability of “no investment” in 2050 is less than five percent, indicating that only a few price constellations exist where no technology has a positive present value. A high probability of “no investment” would imply that unrealistically low prices for electricity have been assumed. For \( P_{\text{CO}_2} = \€25 \), a stronger rise in probability for the CCS technologies is found between 2020 and 2030. Later, saturation is reached. For approximately 20 percent of the price paths, a high value of waiting, combined with the later investment in OFFW is suggested. Considering only the probability distribution in 2050, we find again a high chance for investments in OFFW (up to 65 percent). For the high price scenario \( (P_{\text{CO}_2} = \€45) \), immediate investments in CCS technologies are suggested in 2020. Note that both technologies are assumed to be available from 2020 onwards. Thereby, the HC-IGCC-CCS power plant is preferred in about 80 percent of the price paths. But, also for the high price scenario, we find a significant displacement of the CCS technologies by OFFW in the later time steps.

![Fig. 4. Influence of subsidies for the renewable energies and different initial CO₂ price levels on the investment decision in fossil-fuel-fired power plants with CCS](image-url)
For the case that subsidies are given according to the legislation of the EEG, the model suggests an immediate investment in OFFW for all three carbon permit prices considered. Note that, due to the fact that the decision tree is evaluated from the end to the beginning (roll-up), the investment decisions after 2020 are not affected by the subsidies granted. Differences between the initial CO\textsubscript{2} prices can only be seen in the second time step, for which a high displacement of the OFFW by the CCS technologies is found despite the prevailing subsidies.

5. Conclusion

The present study investigates the potential of CCS for becoming a bridging technology, using a new multi-dimensional, real options approach to evaluate real-world investments. In this evaluation, not only the value of waiting, but also the possibility to choose between various available technologies is accounted for. Two different power plants equipped with CCS (a hard coal-fired IGCC-CCS power plant and a gas-fired combined cycle-CCS power plant) are evaluated individually and in competition with other technologies. For the individual evaluation of the COGAS-CCS power plant, the model predicts an immediate investment in 2020 (the first time when the technology is assumed to be available). The value of waiting for the HC-IGCC-CCS power plant is higher, but also a probability of more than 40 percent for immediate investment is found. However, in competition with other technologies (e.g. conventional HC power plants or wind offshore power plants), the probability to invest in CCS power plants decreases strongly. We find that in the earlier years, the displacement is caused by conventional technologies, whereas the displacement due to the wind offshore power plants is found to take place at later times.

The subsidies for the renewable energies are found to have a strong influence on the investment decision. For all different initial CO\textsubscript{2} allowance price levels, an immediate investment in wind offshore power plants is predicted. Also, in the second time step, i.e. in 2020, an immediate investment in offshore wind is predicted for the low and intermediate CO\textsubscript{2} allowance price scenario. Only for high permit prices, the model suggests to invest in CCS instead of wind offshore power plants.

In conclusion, for the German situation we can state in line with to the studies of Viebahn et al. [2], that the potential of CCS as a bridging technology between the age of fossil-fueled electricity generation and the age of electricity generation by renewable energy technologies is very narrow. However, it should be noted that this finding is based on a model approach which does not distinguish between power plants which can operate on demand and such whose operation time is dependent on external factors like wind or solar irradiation.

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