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# Coal and Gas – From Cradle to Grave with Carbon Capture and Storage An Efficiency Analysis

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# Coal and Gas – From Cradle to Grave with Carbon Capture and Storage

An Efficiency Analysis

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**Abstract**

*Existing studies on Carbon Capture and Storage (CCS) only focus on costs and carbon dioxide ($CO_2$ ) reduction that arise at the power plant and geological storage. These studies do not consider additional expenses and emissions at the input and output pathways. Consequently, we use a simulation model containing input data from different studies to estimate the cradle-to-grave costs of avoided carbon dioxide. We show that the true costs vary between 70 and 90 US-Dollars per ton of $CO_2$ . Additional sensitivity analyses support the results because they are robust against different parameter adjustments. Because it is not evident whether CCS is an efficient mitigation option, it is compared to a variety of renewable energy sources. Thus, it is cheaper to avoid one ton of $CO_2$ by means of wind energy, but costs arising from the use of solar energy are much higher.*

*Keywords: CCS, coal, gas, cradle-to-grave, climate change, energy, efficiency analysis, renewables.*

# 1 Introduction

For more than 200 years, energy production by means of fossil fuels, such as coal, oil and natural gas, has been the spine of industrial production and one of the major driving forces in economic growth. This positive effect is offset by an increase of greenhouse gas emissions, which unavoidably emerge as a side-product from burning these energy sources. The consequences of a growing atmospheric $CO_2$ concentration, which comes with a rise in the earth's surface temperature by more than $2K$, are hard to measure from an economic perspective. However, this environmental trend is linked to droughts, flooding, species extinctions and other natural disasters (see Stern (2007), IPCC (2014)).

Due to the effects of climate change, carbon capture and storage (CCS) technology–which is seen as a technology that can bridge the gap to a world full of renewable energy sources–is receiving increasingly more attention in recent greenhouse gas mitigation studies. CCS technology consists of three process steps. In the first step, carbon dioxide has to be captured either by separation from post-combustion flue gas or by means of pre-combustion or oxyfuel technology. Afterward, the captured greenhouse gas has to be compressed and transported via pipeline or barge to suitable long-term storage. Because of different demands regarding safety, cost effectiveness and accessibility, only saline aquifers and depleted oil and gas fields are appropriate storage modes. Considering the chance of enhanced oil and gas recovery, it is even possible to make revenue by selling captured carbon dioxide.

To make a statement about the efficiency of CCS technologies, the costs and emission savings of each process step have to be taken into account. In fact, it is important to include indirect effects, which are linked to adopting new technology and emerge along the full chain of electricity generation. The efficiency penalty that is caused by a plant's CCS retrofit is a crucial point because it has two side-effects. First, the combustion emissions rise due to the lower efficiency factor. Second, the higher demand for fossil fuels comes with an increase in transport-specific greenhouse gas emissions. Additionally, carbon dioxide emissions arising from transportation and storage have to be taken into account. Unfortunately, existing studies on the efficiency of CCS technologies only focus on some parts of the full process. They do not consider additional emissions and costs along the input and/or output pathways that have a major impact on the entire efficiency evaluation. Thus, the avoidance costs that arise from a cradle-to-grave perspective are still unknown.

To estimate the true costs of carbon dioxide avoided, we built a Vensim model[1], which contains input data from different existing studies. This model aims to capture the most important cost and emission parameters along the full chain of electricity generation. In this study, our model focuses on retrofitting existing power plants with CCS technology, but it can easily be adjusted to calculate different settings. Because it is very hard to compare simple emission and cost data, a key figure that combines both crucial dimensions is needed. According to the often-used figure "costs of carbon dioxide avoided", we introduce the so-called "normalized costs of cumulative reduction of carbon dioxide emission intensity" (CCR). It is defined as the quotient of total additional full-chain costs caused by a power plant's CCS retrofit or by the integration of another environmentally friendly technology and the net-cradle-to-grave emission savings. The knowledge about this figure is of high importance because it serves as a benchmark

[1] Vensim is a System Dynamics that allows for calculating fluxes and stocks by graphical modeling

in the discussion on future welfare-loss caused by today's emissions. We show that the CCR for CCS retrofit varies between 70 and 90 $\$/t\,CO_{2eq}$, depending on the fossil fuel that is used for electricity generation. To test the validity of the results, we perform a sensitivity analysis concerning uncertainties within the input parameters and environmental conditions. It becomes obvious that our results are robust against different parameter adjustments.

Because it is not evident whether CCS technology is an efficient mitigation option, it is compared to a variety of renewable energy sources. We demonstrate that CCS is superior to photovoltaics but inferior to wind and hydropower.

The remainder of this paper is organized as follows. In section two, we sum up the results of some existing studies that calculate the cost of carbon dioxide avoided by means of retrofitting existing power plants with amine based end-of-pipe CCS technology. To understand the importance of the input and output pathways, section three illustrates the entire CCS process chain from cradle to grave. In addition to that, the most important cost and emission estimates that are linked with each process step are outlined. In section four, the general Vensim setup containing the input parameters and calculation formulas is introduced. Moreover, we show the model's results and their robustness against parameter adjustments. Section five serves as an inter-technological comparison between CCS and other green technologies. Section six concludes this paper.

# 2 State of Knowledge

CCS technology is subject to many recent carbon dioxide mitigation studies. Thus, this section serves as a short survey of different CCS cost-estimating studies. For each study, the assumptions for calculating the costs of carbon dioxide avoidance and outcomes, as well as the deficits regarding a full chain analysis, are noted.[2]

Rubin and Rao (2002) use an Integrated Environmental Control Model (IECM) with an additional $CO_2$ module to estimate the costs and emissions that arise from retrofitting a coal-fired power plant. Because they focus on an existing power plant, a monoethanolamine-based, post-combustion absorption system has to be used. It is as effective for dilute $CO_2$ streams as the only proven end-of-pipe technology. Furthermore, it is assumed that there is no power upgrade to compensate the eciency penalty in net power which comes along with the operation of the capture system. To gather uncertainties input parameters are represented by a probability distribution. Additionally, it is assumed that amine system removes 90% of the flue gas $CO_2$ with a purity of at least 99%. Using this framework they calculated the costs of carbon dioxide avoided which is defined as the following:

$$\textit{Cost of } CO_2 \textit{ Avoided } [\$/tCO_2] \;=\; \frac{SC[\$/MWh]_{CCS} - SC[\$/MWh]_{ref}}{SE[tCO_2/MWh]_{ref} - SE[tCO_2/MWh]_{CCS}}$$

[2]Please note that all costs are in US-$ (2015), inflation-adjusted by *www.usinflationcalculator.com.*

Where SC stands for "Specific Costs of Electricity" and SE denotes the "Specific $CO_2$ Emissions". It is shown that the cost of $CO_2$ avoidance ranges from 77.2 $\$/t\,CO_2$ to 155 $\$/t\,CO_2$ depending on the existence and performance of flue gas desulfurization systems, which have a major impact on the monoethanolamine uptake rate. Although these costs seem to be high neither coal-input nor $CO_2$-output pathways were taken into account. Thus, these results are only relevant for plant owners and do not reflect the true economic costs.

In a later study, Rubin et al. (2007) used the IECM model again but partly changed the settings and enlarged the perspective on gas-fired power plants. In detail, they assumed the retrofitted coal-fired plant to be power adjusted to supply the same energy as the reference plant, whereas the gas-fired plane was not. Moreover, the importance of a pipeline transport (161 km) and geological storage of the captured $CO_2$ are considered. They especially assume transport costs of 3.7 $\$/t\,CO_2$, geological storage costs of 6 $\$/t\,CO_2$ and enhanced oil recovery (EOR) revenues of 18 $\$/t\,CO_2$. Hence, they find that taking transport and storage into account increases the cost of electricity (COE) in the case of using a saline aquifer for storage by 4-10%, but decreases COE by 7-18% if there is a chance to sell $CO_2$ to an EOR project. The (local) costs of $CO_2$ avoided at the power plant are highest for the gas-fired plant and total 75.2 $\$/t\,CO_2$. If the additional expenses/credits for transport and storage are included, this figure either increases up to 87 $\$/t\,CO_2$ or decreases to 53.4 $\$/t\,CO_2$, depending on the type of storage. Due to the proportionally cheap coal and high carbon emissions in comparison to gas, the costs of $CO_2$ avoided are lower in the case of a coal-fired plant. For the power plant itself, they amount to 59.7 $\$/t\,CO_2$ and rise to 73.2 $\$/t\,CO_2$, assuming a geological storage without EOR. Due to the high amount of captured $CO_2$, huge revenues result if it can be sold to EOR projects. Thus, the cost of $CO_2$ avoided is at a very low level of only 34.9 $\$/t\,CO_2$. Although the output pathway cost perspective was considered, the additional emissions and the entire input pathway were neglected. Consequently, these results are a better measure in estimating the true costs than the results of early CCS studies, but they are still insufficient.

The IEAGHG (2011) follows a similar approach. The organization estimates the abatement costs of $CO_2$ for a variety of post-combustion retrofitted power plant settings, but it also includes the $CO_2$ emission costs that arise from buying emission certificates. Hence, their estimated costs for reducing carbon dioxide emissions benefit from high certificate prices, which do not exist today. Nevertheless, they found that abatement costs for coal-fired power plants and geological storage range between 72.3 and 101 $\$/t\,CO_2$, whereas costs for gas-fired plants appear to be significantly higher, with prices between 99.8 and 131.4 $\$/t\,CO_2$, depending on the type of power adjustment. To show why it is crucial to argue with these estimates in economic debates, the following section explains the importance of taking costs and emissions, along with input and output pathways, into account.

# 3 Cradle-to-Grave

The economic efficiency analysis of a new technology needs to be based on a cradle-to-grave perspective to capture the most side and rebound effects, which directly emerge in the case of adopting the technology. Therefore, this section is divided into three parts: the input pathway, the power plant itself and the output pathway. Within these subsections, the most important cost and emission estimates for each process step of energy production by means of coal- and gas-fired plants are outlined. The parameters are taken from several studies that are appropriate within this context and serve as inputs for the following model.

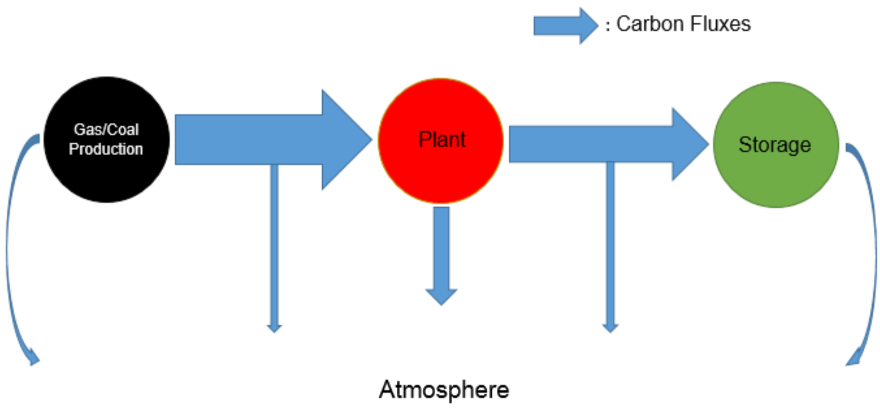


Figure 1: cradle-to-grave perspective

## 3.1 Input pathway

Although the input pathway is of high relevance when considering the impacts of a post-combustion CCS retrofit, it has not yet found its way into all recent CCS literature. Its importance arises from the power plants' efficiency penalty, which is caused by the energy consumption of the $CO_2$ capture system. If there is an unchanged energy demand in the grid, the power plant either has to be power adjusted or another power plant has to be built. Both options increase the total demand for fossil fuels and the emissions caused by coal and gas production and transportation. Whereas the cost effect can be easily captured by rising fuel costs per $MWh$, which was already done in the studies mentioned above[3], it is hard to compute production and transportation emissions.

Koornneef et al. (2008) estimated the emissions along the coal supply chain and figured out that the production of coal adds $0.034\,tCO_{2eq}/MWh_{el}$ standardized on a plant efficiency of 40% to combustion emissions. Additionally, transporting coal over an average distance further adds $0.027\,tCO_{2eq}/MWh_{el}$. Expanding the perspective to the total coal supply chain shows that

[3]In the case of a thermal power adjustment, the rise in costs can be estimated by calculating the additional fuel that is needed to produce the same amount of energy given the original eciency factor minus the efficiency penalty.

all in all, there are specific emissions of approximately $0.081\,tCO_{2eq}/MWh_{el}$, which have to be considered because the efficiency penalty causes higher total production and transportation emissions.

Gas can be produced in two different ways: ordinary production and fracking. In the case of ordinary gas production, the amount of emitted greenhouse gases is higher than that in the case of fracking. Furthermore, the leakage of methane during transport is crucial because its global warming potential is more than 20 times higher than $CO_2$. Weber and Clavin (2012) used six previous studies in a Monte Carlo simulation to obtain a best estimate for greenhouse gas emissions along the gas input pathway. They came up with the following result: Ordinary production plus transport comes with $16\,g\,CO_{2eq}/MJLHV$, whereas fracking plus transport only causes $14.6g\,CO_{2eq}/MJLHV$ . Under the assumption of a combustion efficiency of 40%, this value corresponds to specific emissions of $0.144\,tCO_{2eq}/MWh_{el}$ and $0.131\,tCO_{2eq}/MWh_{el}$, respectively.

## 3.2 Power plant

As already mentioned, the retrofit of an existing power plant with post-combustion CCS technology has a major impact on efficiency and, thus, on combustion emissions. Moreover, fixed costs and variable costs for operation, fuel and maintenance rise. Concerning the shrinking marginal profit of ecological investments, the cost of $CO_2$ avoidance is expected to be higher for gas-fired plants than for coal-fired plants. This assumption is based on the fact that electricity produced by means of burning gas is a comparatively clean technology, which makes it difficult to turn it into an even more eco-friendly technology. To include this fact in the analysis and to be able to make proposals for energy policies, the CCS efficiency of a poorly retrofitted coal power plant is compared to a gas-fired plant with an almost ideal post-combustion system. Among others, these two types of power plants are given by the IEAGHG (2011).

The reference coal plant has a maximum thermal power of $2000\,MW_{th}$ and provides an electricity output of $800\,MW_{el}$ due to an efficiency factor of 40%. The amount of $CO_2$ produced per hour totals $660\,tCO_2$ at a full load, which corresponds to specific emissions of $0.825\,tCO_2/MWh_{el}$. The variable, fixed and fuel costs total $38.7\,\$/MWh_{el}$. The total capital expenditure that comes with boiler heat and power-matched retrofit is approximately $1899.2\,m\$$. Despite this high investment, the plants suffers from an efficiency penalty of 12.5% due to the high energy demand of the post-combustion capture system. Consequently, this penalty causes an increase in fuel consumption by 45%. Additionally, the operation of the capture system increases variable and fixed costs. Nevertheless, a 90% reduction of $CO_2$ within flue gas can be achieved. Because of higher fuel consumption, this capture rate results in net greenhouse gas emissions that are 85% lower than in the reference case.

The reference gas plant possesses an efficiency of 54%, which reduces the thermal power to less than $1500\,MW_{th}$ if a maximum power output of $800\,MW_{el}$ is needed. Based on this relatively low fuel demand, specific emissions are down to only $0.389\,kg\,CO_2/MWh_{el}$, which is less than half of the coal plant's emissions. A power-matched retrofit may even decrease the greenhouse gases to less than $0.07\,kg\,CO_2/MWh_{el}$ because of a very small efficiency penalty of 7.1% and a high capture rate of 85%. This ecological impact causes a significant increase in electricity costs. This is problematic because absolute $CO_2$ avoidance is rather low. Therefore, the local costs of $CO_2$ avoided are high in comparison to coal-fired plants. Regarding transportation and storage, it is questionable whether the low amount of captured $CO_2$ may overcompensate for this effect in the end. Hence, the output pathways' influence on the total emission savings and costs also has to be taken into account.

## 3.3 Output pathway

After the production of electricity, captured CO2 has to be carried to a suitable reservoir. Both process steps of the output pathway–transport and storage–are unavoidably connected to additional costs and emissions. For carriage, two means of transportation are available: the pipeline and the barge. Using the pipeline creates two more sources of emissions. First, there may be a leakage of $CO_2$ that causes the pipeline $CO_2$ output flow to be smaller than the input. Second, additional power for pumping et cetera is needed to carry $CO_2$ from the plant to the reservoir. According to the IPCC (2005), these two sources cause additional greenhouse gas emissions of one to two percent of the carried fluid per 1000 $km$. Because of the high number of factors that have an impact on the transportation costs via the pipeline, such as the urban or rural landscape, safety arrangements, size, mass flow and so on, in this study, constant specific costs of $5\,\$/(tCO_2 \cdot 250km)$ are assumed to keep things simple. Because barges are often claimed to cause higher additional emissions of at least 2.5% of the carried carbon dioxide mass per 200 $km$, whereas they are even more expensive (approximately $20\,\$/(tCO_2 \cdot 250km)$ more in comparison to the pipeline transportation), they are neglected in this study. When the carried $CO_2$ arrives at the reservoir, the costs for storage and/or revenues for selling the $CO_2$ to EOR projects have to be taken into account. The storage costs consist of different components, such as exploration, building infrastructure and monitoring the stored carbon dioxide. Anderson and Newell (2004) estimate the costs for storage of $CO_2$ in saline aquifers and find a range between 2.5 and $22.6\,\$/tCO_2$ with a base case estimate of approximately $5\,\$/tCO_2$. Despite the often already existing infrastructure, exploited oil and gas fields come with higher base case storage costs of approximately $7.5\,\$/tCO_2$ because they suffer from a lack of economies of scale, as their effective storage is comparatively small. Nevertheless, selling $CO_2$ to EOR projects may lead to revenues that exceed the costs for storage, so there are net benefits of storage in the end. Although the captured $CO_2$ is located in a geological formation hundreds of meters below the surface, there is no absolute certainty about its disposition. Klusman (2003) shows that leakage of an EOR field in Colorado is less than 0.00076% per year. Despite the fact that this loss of prior avoided $CO_2$ appears to be negligible, it has to be considered in a cradle-to-grave perspective, especially if there are higher rates of leakage that may be undetected.

# 4 Model

The following model aims to capture the most important effects of a cradle-to-grave efficiency analysis for gas- and coal-fired plants to calculate the "normalized costs of cumulative reduction of carbon dioxide emission intensity". It is equivalent to the costs of carbon dioxide avoided but allows for taking the full chain into account[4]. Thus, we explain the model framework, including the input parameters in a first step, and note the base scenario results. In a further section, we test the sensitivity of the CCR regarding variation in the input parameters.

## 4.1 Framework

The CCR is defined as the following:

$$CCR[\$/tCO_2] \;=\; \frac{STC[\$/MWh]_{CCS} - STC[\$/MWh]_{ref}}{STE[tCO_2/MWh]_{ref} - STE[tCO_2/MWh]_{CCS}}$$

(STC: specific total costs[$\$/MWh$], STE: specific total emissions[$tCO_2/MWh$], ref: reference plant without CCS retrofit, CCS: scenario taking a CCS retrofit into account)

To calculate the CCR, the specific total costs and emissions that arise from a cradle-to-grave perspective have to be computed. The specific total costs arise from the sum of the total local power plant costs (PC[$]) and the obligatory $CO_2$ transportation (CTC[$]) and storage (SC[$]) costs divided by the total amount of energy (E[$MWh$]), which is supplied over the period under consideration. The PC mainly depend on the cost of electricity (COE[$\$/MWh$]) and the capacity factor (CF[ ]):

$$PC \;=\; \int COE(t) \cdot CF(t) \cdot max.\ power\ output\ \mathrm{d}t$$

The COE are given by the following formula considering the total capital expenditure (CAPEX[$]), annuity factor (AF[$1/a$]), yearly fixed costs (YFC[$\$/a$]), variable costs(VC[$\$/MWh$]), fuel costs (FC[$\$/MJ$]) and power plant efficiency ($\eta$[ ]):

$$COE(t) \;=\; \frac{CAPEX \cdot AF + YFC(t)}{8760 \cdot CF(t) \cdot max.\ power\ output} + VC(t) + \frac{3600 \cdot FC(t)}{\eta}$$

The transportation costs of $CO_2$ arise from the product of specific transportation costs (SCTC[$\$/(\mathrm{t}CO_2 \cdot km)$]), the captured amount of $CO_2$ (CAC[t$CO_2$]) and the distance of transportation (S[$km$]):

$$CTC \;=\; \int SCTC(t) \cdot S \cdot CAC(CF(t))\ \mathrm{d}t$$

Similarly, the storage costs can be calculated with the help of the specific storage costs (SSC[$/t$CO_2$]):

$$SC \;=\; \int SSC(t) \cdot CAC(CF(t))\ \mathrm{d}t$$

[4]From now on, the CCR and costs of carbon dioxide avoided are used synonymously.

Because the CCR is supposed to reflect the net present value of carbon dioxide avoidance costs, all (specific) cost figures have to be computed via an differential equation[5]:

$$\dot{C} \;=\; \left(\frac{1+\pi_C(t)}{1+i(t)} - 1\right) \cdot C$$

(C: cost figure, $\pi$: figures inflation, $i$: interest rate)

In the case of the reference plant, the specific total emissions arise from the sum of combustion (CE[$tCO_2$]) and fuel transport emissions (FTE[$tCO_2$]) divided by the total amount of energy. To compute the specific total emissions for the CCS-retrofitted plant as well as the additional emissions arising from $CO_2$ transport (CTE[$tCO_{2eq}$]), the emissions savings represented by the storage's filling level (SF[$tCO_2$]) have to be taken into account. The specific combustion emissions (SCE[$tCO_2/MWh_{el}$]) and the power plant's output are insufficient to compute the combustion emissions because the ratio of the efficiency with which the specific emissions were calculated ($\eta_{SCE}$) and the real plant efficiency($\eta_{plant}$) has a major impact:

$$CE \;=\; \int SCE \cdot \frac{\eta_{SCE}}{\eta_{plant}} \cdot max.\ power\ output \cdot CF(t)\ \mathrm{d}t$$

The same argument holdss for the fuel transport emissions because a lower plant efficiency causes an increase in effective specific transport emissions (SFTE[$tCO_2/MWh_{el}$):

$$FTE \;=\; \int SFTE \cdot \frac{\eta_{SFTE}}{\eta_{plant}} \cdot max.\ power\ output \cdot CF(t)\ \mathrm{d}t$$

Greenhouse gases that are emitted because of $CO_2$ transport do not directly depend on the power plant's efficiency anymore. The most important variables are the specific $CO_2$ transport emissions (SCTE[$1/km$]) and distance:

$$CTE \;=\; \int SCTE \cdot S \cdot CAC(CF(t))\ \mathrm{d}t$$

As mentioned above it is important to include the storage's leakage if higher rates of $CO_2$ loss are considered. Thus the storages filling has to be calculated by the following differential equation, which contains the dimensionless rate of leakage (RL[ ]):

$$\dot{SF} \;=\; CAC(CF(t)) - RL \cdot SF$$

To solve the differential equations, Vensim, a system dynamics software tool that allows for modeling the system of equations as a system of flows and stocks, is used. A graphical representation can be found in Appendix A. The model's input data comply with the figures mentioned in section 3. Particularly in the base case, a levelization factor of 1.0 is assumed, which means that the year-by-year increase in all prices equals the interest rate. In addition, the period of considerations consists of 25 years for the coal-fired plant and 20 years for the gas-fired plant. Concerning the output pathway, a carbon dioxide transport distance of 250 $km$ and an annual storage loss of 0.001% are taken into account. Detailed tables containing all input data are reported in Appendix B.

[5]The CAPEX annuity has also to be discounted but $\pi_{\text{CAPEX}} = 0$

## 4.2 results

The results for the reference plant models without CCS are the following: The specific total emissions of the coal-fired plant are almost double the gas-fired plant's emissions, with $0.92\, tCO_{2eq}/MWh$ and $0.5\, tCO_{2eq}/MWh$. The total specific costs sum up to $39\,\$/MWh$ for coal and $65\,\$/MWh$ for gas plants due to comparatively high gas prices. Considering the CCS retrofit, the total specific emissions decline significantly in both cases, with advantages on the part of the coal-fired plant. They decrease by more than 70% in the case of coal and by more than 60% in the case of gas. A graphical representation is reported in figure 2.

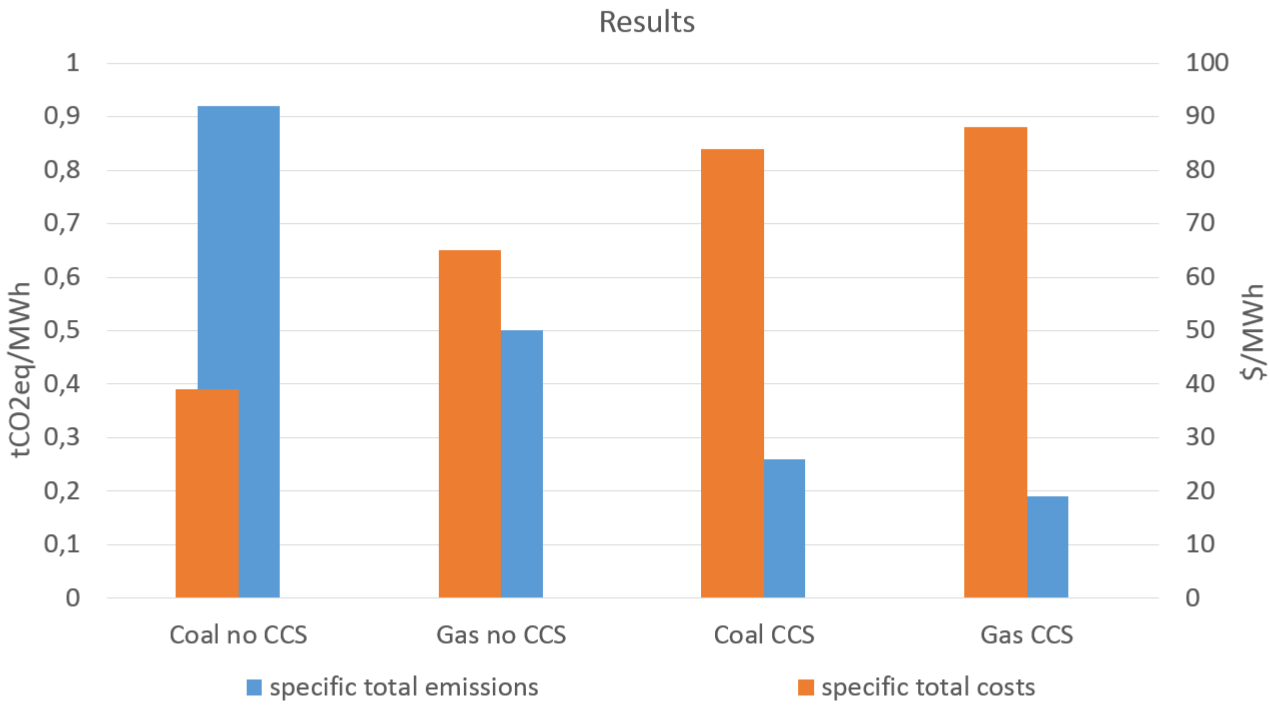


Figure 2: power plant results

Although the absolute increase in specific total costs is lower for gas plants (increase by $45\,\$/MWh$ vs. $23\,\$/MWh$), the CCRs are considerably higher because of lower absolute reduction in carbon dioxide emissions. They mount up to approximately $76\,\$/tCO_{2eq}$ for electricity production by means of gas, and $69\,\$/tCO_{2eq}$ by means of coal. Thus, the prior assumption of decreasing marginal profits of environmental technologies appears to be proven. A graphical representation is shown in figure 3.

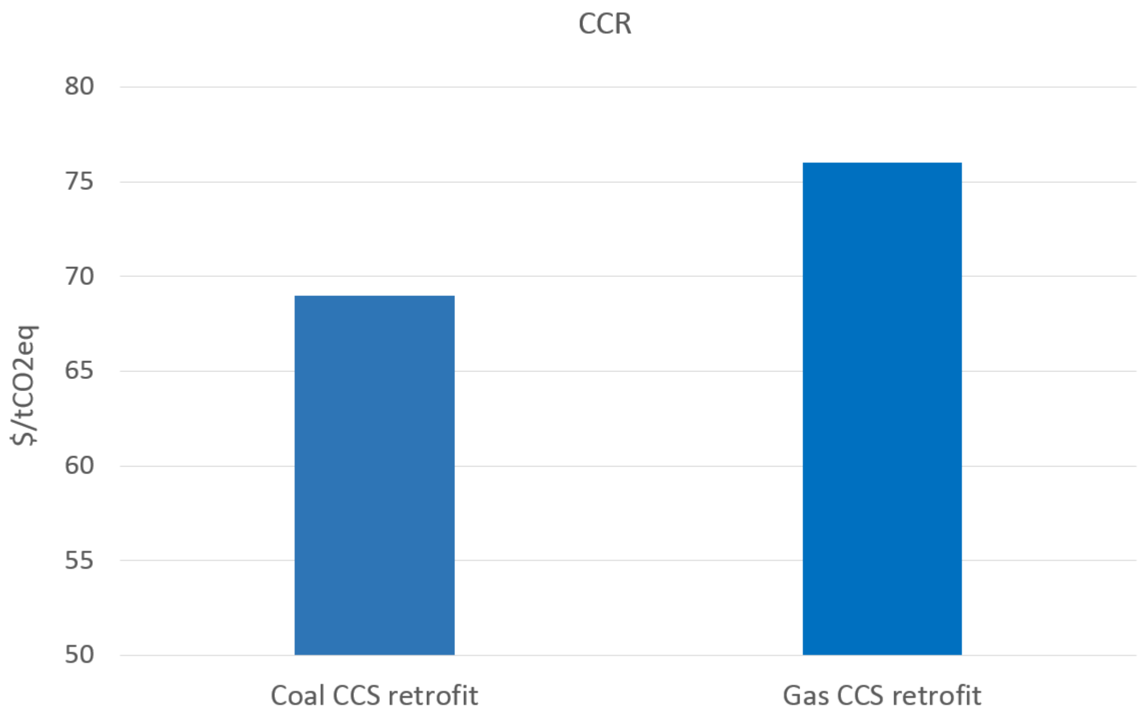


Figure 3: base scenario CCR

## 4.3 sensitivity analysis

The objective of this section is to analyze the influence of variation in the input parameters on the CCR. Therefore, a step-by-step change of single parameters is performed, whereas only the most important results are described in detail. A tabular summary of the most tested impacts is provided in Appendix C.

First, a poorly performed retrofit may cause a higher efficiency penalty than assumed in the IEAGHG (2011) models. Therefore, efficiency of the retrofitted power plants is reduced in our model by two percentage points. Due to high gas prices, this variation has a stronger impact on the CCR of gas-fired plants than on that of coal-fired plants. They increase by approximately 15 $\$/tCO_{2eq}$ and 11 $\$/tCO_{2eq}$.

Second, the trend of prices is very uncertain. To include a real price rise, the interest rate is lowered at 3%, whereas all inflation parameters are kept at 5%, which corresponds to a rise in real prices by approximately 2% annually. This change in cost parameters causes a CCR of approximately 86 $\$/tCO_{2eq}$ for gas- and 82 $\$/tCO_{2eq}$ for coal-fired plants.

Furthermore, a 10% increase in fuel prices is modeled. The outcomes are less strongly affected when considering a two percentage point additional efficiency penalty, but note the gas plant's sensitivity again regarding fuel prices. The gas CCR increased by 2 $\$/tCO_{2eq}$, and the coal's CCR increased by only 1 $\$/tCO_{2eq}$.

As mentioned above, there might be a chance to sell the captured $CO_2$ to EOR projects and yield good revenues. A net return of $10\,\$/tCO_2$ has a major positive effect on parts of the coal-fired plants because there is a higher amount of captured carbon dioxide. The CCRs go down to approximately $44\,\$/tCO_{2eq}$ for coal- and $57\,\$/tCO_{2eq}$ for gas-fired plants.

Another crucial point is the capacity factor. The CCS retrofit of power plants comes with a rise in the short-term costs of electricity. Therefore, it is harder to sell the produced electricity on stock markets, and consequently, the capacity factor decreases. To capture this effect, the capacity factor of the CCS plants is cut at 60%. Because of the low amount of supplied energy and the accordingly intense impact of CAPEX and fixed costs, the CCRs increase dramatically. In the case of gas, they mount up to approximately $91\,\$/tCO_{2eq}$, and in the case of coal, they mount up to more than $82\,\$/tCO_{2eq}$.

Finally, most studies do not consider storage leakage when estimating the costs of carbon dioxide avoided. This is not problematic if very low rates of leakage are assumed. However, according to Minh and Keith (2003), geological storage with an annual leakage of 0.1% can be rated as safe. Hence, we consider a leakage rate of 0.1%, observing a period of 100 years. Neglecting a social rate of discount, the total specific emissions rise to $0.22\,tCO_{2eq}/MWh$ (gas) and $0.35\,tCO_{2eq}/MWh$ (coal) corresponding to an increase in the CCR to $85\,\$/tCO_{2eq}$ (gas) and $79\,\$/tCO_{2eq}$ (coal).

Regarding the additional results, it becomes obvious that the CCR is rather robust against variations in the input parameters. Hence, the true costs of $CO_2$ avoided range between 70 and $90\,\$/tCO_{2eq}$, with advantages on the part of coal-fired plants. Nonetheless, it is not clear whether CCS technology is an efficient carbon dioxide mitigation technology. To answer this question, the CCR is computed for some renewable energy sources.

# 5 Inter-technological comparison

Hydropower stations, wind energy converters, geothermal stations and photovoltaics are the most-often discussed renewable energy sources. Therefore, this section lists some cost and emission estimates of renewable energy sources to calculate the costs of carbon dioxide avoidance in the case of conventional fossil fuel-fired plants being replaced by renewables. A tabular summary of these results is given in Appendix D. The means of cost and emission estimates of renewable energy sources are given by Evans et al. (2009). Due to the energy-intensive manufacturing process, which has an energy consumption of at least $13.000\,kWh$ per installed $kW$-peak (see Varun et al. (2009)), photovoltaics come with comparatively high, specific life cycle emissions of approximately$0.09\,tCO_{2eq}/MWh$ and electricity costs of $264\,\$/MWh$. Thus, the price of carbon dioxide avoided is enormously expensive, amounting to more than $270\,\$/tCO_{2eq}$ for a replacement of coal and $490\,\$/tCO_{2eq}$ for gas.

According to Varun et al. (2009), the manufacturing of an average-sized wind energy converter requires $12,000\,MWh$ of primary energy. Nevertheless, specific emissions and costs are rather small because they can convert more than 50% of wind's kinetic energy into electricity. Assuming average emissions of $0.025\,tCO_{2eq}/MWh$ and specific costs of $77\,\$/MWh$ in both cases, the costs of carbon dioxide avoided are lower than those using CCS technology (coal: approximately $42\,\$/tCO_{2eq}$; gas: approximately $25\,\$/tCO_{2eq}$).ßß The electricity costs arising from the use of geothermal stations are similar to the energy production by means of the wind converter. Nevertheless, the costs of carbon dioxide avoided are higher in both cases (replacement of coal: approximately $50\,\$/tCO_{2eq}$; replacement of gas: approximately $36\,\$/tCO_{2eq}$) because there are more greenhouse gas emissions during the plants' life-cycle, and the efficiency of converting heat into electricity is low due to the bad Carnot factor, which results in specific emissions of approximately $0.17\,tCO_{2eq}/MWh$.

The transformation of potential energy into electricity by means of hydropower stations ordinarily has an efficiency of 90%, which is the highest of all renewable energy sources. In addition, the construction and operation of the station itself come with very low emissions. Most cradle-to-grave greenhouse gas emissions are caused by flooding, the involved anaerobic degradation and reduced ability of the biological environment to capture carbon. After all, average specific emissions and costs of $0.04\,tCO_{2eq}/MWh$ and $55\,\$/MWh$ are taken as reference value. Thus, the CCRs are low in the case of replacing coal-fired plants (less than $20\,\$/tCO_{2eq}$) or nonexistent in comparison to gas-fired plants because hydropower stations are advantageous regarding the costs of electricity and specific emissions.

Despite the comparatively low avoidance costs of wind and water energy stations, it has to be considered that the supply of energy is extremely weather-dependent and, thus, inflexible. Furthermore, if there are extreme weather conditions and a low electricity demand at the same time, there must be a possibility to store energy to use it at times of higher demand. Due to energy losses and rising costs for storage and energy-grid management, the costs of carbon dioxide avoided may increase.

# 6 Conclusion

Recent studies on efficiency of adapting CCS technology only focus on local costs of carbon dioxide avoidance at the power plant. This perspective neglects impacts that are caused by CCS along the in- and output pathways. Thus, the true costs of avoiding greenhouse gases are still unknown. In this paper the importance of using a fossil fuel cradle-to-grave perspective is described and included into a Vensim model in order to estimate the "normalized costs of cumulative reduction of carbon dioxide emission intensity" which can be interpret as extension of the common figure "cost of carbon dioxide avoided". The results are the following: it is cheaper to avoid one ton of greenhouse gases by retrofitting existing coal plants than by retrofitting existing gas plants. Although this fact seems to be inconsistent at a first glance, because gas fired plants without CCS technology are often called "clean" already, it is not. This is caused due decreasing marginal profits of eco-friendly technologies. Therefore, it is more efficient to turn a dirty technology into a green one than making a green technology even more cleaner. The advantage of coal fired power plants as well as the magnitude of the CCR were confirmed in a sensitivity analysis. At this point it has also to be mentioned that there might be an even bigger benefit on side of coal fired plants if district heating is factored into the model, too.

In order to answer the question whether the CCS technology is an efficient carbon dioxide mitigation technology it is compared to a variety of renewable energy sources. In the inter-technological comparison it becomes obvious that CCS is only superior to photovoltaics if side effects of renewables are neglected. Against the background of saving greenhouse gases it is shown, furthermore, that it is more efficient to replace gas instead of coal fired plants by renewables.

Despite the fact that estimates for true costs of carbon dioxide avoidance are known from now on it is still questionable if it is useful to adopt these technologies because estimates on carbon caused damages on future GDP diverge dramatically. Assuming today's social costs of about 90$ per ton of carbon dioxide (see Stern (2007)), from an economic perspective, all referred technologies but photovoltaics seem to be suitable mitigation options.

# A Vensim models

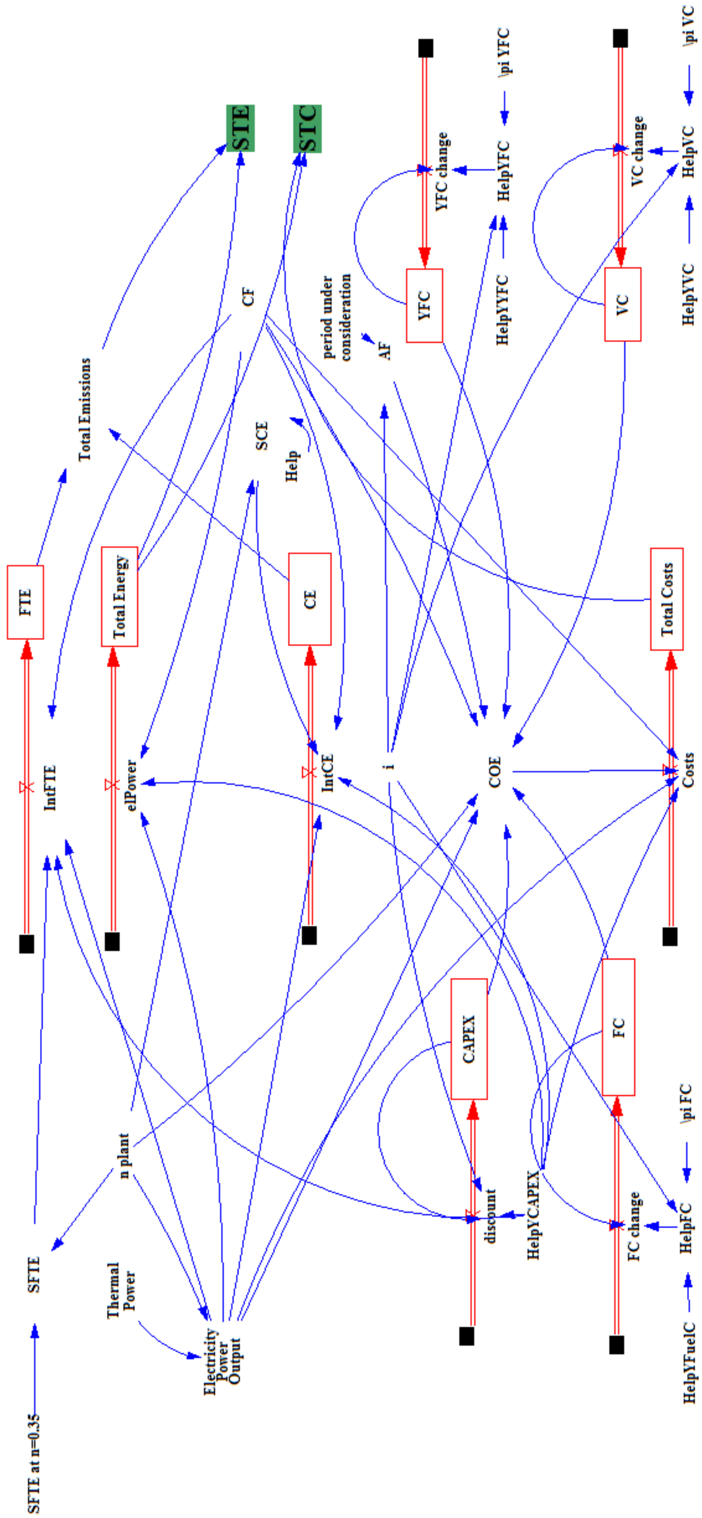


Figure 4: reference plant without CCS

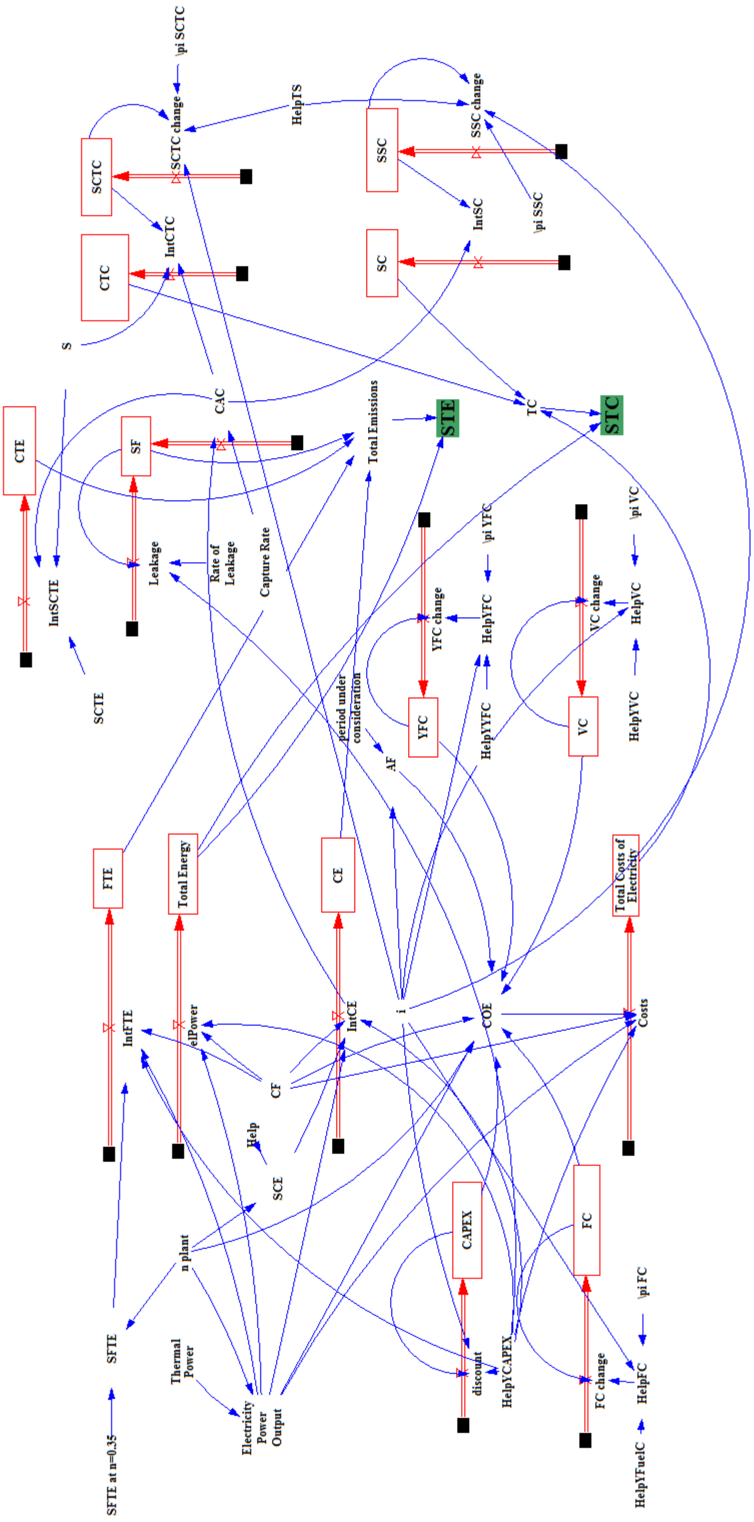


Figure 5: CCS retrofit

# B Input data

| | **coal** | **gas** |
|---|---|---|
| **Power data** | | |
| thermal power | 2000 $MW$ | 1481.5 $MW$ |
| efficiency | 40% | 54% |
| max. el. power output | 800 $MW$ | 800 $MW$ |
| capacity factor | 80% | 80% |
| **Emission data** | | |
| combustion emissions | 0.825 $tCO_2/MWh$ | 0.389 $tCO_2/\ MWh$ |
| fuel transport emissions | 0.095 $tCO_{2eq}/MWh$ | 0.107 $tCO_{2eq}/MWh$ |
| **Cost figures** | | |
| CAPEX | 0$ | 0$ |
| fuel costs / inflation | 10.5 $\$/MWh_{th}$ / 5% p.a. | 31.5 $\$/MWh_{th}$ / 5% p.a. |
| variable costs / inflation | 5.25 $\$/MWh$ / 5% p.a. | 3.15 $\$/MWh$ / 5% p.a. |
| annual fixed costs / inflation | 41.8$m$$ / 5% p.a. | 21.2$m$$ / 5% p.a. |

Table 1: base case input data – plants without CCS

| | **coal** | **gas** |
|---|---|---|
| **Power data** | | |
| thermal power | 2906.6 $MW$ | 1704.7 $MW$ |
| efficiency | 27.5% | 46.9% |
| max. el. power output | 800 $MW$ | 800 $MW$ |
| capacity factor | 80% | 80% |
| **Emission data** | | |
| combustion emissions | 1.2 $tCO_2/MW$h | 0.448 $tCO_2$ |
| fuel transport emissions | 0.138 $tCO_{2eq}/MWh$ | 0.123 $tCO_{2eq}/MWh$ |
| capture rate | 90% | 85% |
| Specific $CO_2$ transport emissions | 1% per 1000$km$ | 1% per 1000$km$ |
| storage loss rate | 0.001%/$a$ | 0.001%/$a$ |
| **Cost figures** | | |
| CAPEX | 2.388$m\$/MW$ | 1.034$m\$/MW$ |
| fuel costs / inflation | 10.5 $\$/MWh_{th}$ / 5% p.a. | 31.5 $\$/MWh_{th}$ / 5% |
| variable costs / inflation | 10.9 $\$/MWh$ / 5% p.a. | 4.7 $\$/MWh$ / 5% |
| annual fixed costs / inflation | 71.8 $m$$ / 5% p.a. | 33.5 $m$$ / 5% p.a. |
| $CO_2$ transport costs / inflation | 10 $\$/(tCO_2 \cdot 1000\,km)$ / 5% p.a. | 10 $\$/(tCO_2 \cdot 1000\,km)$ / 5% p.a. |
| storage costs / inflation | 5 $\$/tCO_2$ / 5% p.a. | 5 $\$/tCO_2$ / 5% p.a. |

Table 2: base case input data – CCS retrofitted plants

# C Base case results and sensitivity analysis

| | coal | gas |
|---|---|---|
| **No CCS** | | |
| STE | $0.92\, tCO_{2eq}/MWh$ | $0.5\, tCO_{2eq}/MWh$ |
| STC | $39\,\$/MWh$ | $65\ \$/MWh$ |
| **CCS** | | |
| STE | $0.26\, tCO_{2eq}/MWh$ | $0.19\, tCO_{2eq}/MWh$ |
| STC | $84\,\$/MWh$ | $88\,\$/MWh$ |
| **CCR** | $69\,\$/tCO_2$ | $76\,\$/tCO_2$ |

Table 3: Base case results

| **variation input parameters** | **CCR** [**\$**$/tCO_{2eq}$] | |
|---|---|---|
| | **coal** | **gas** |
| efficiency penalty increase (+2%) | 80 | 91 |
| interest rate 3% | 82 | 86 |
| fuel costs +10% | 70 | 79 |
| CAPEX +10% | 71 | 78 |
| fixed costs +10% | 69 | 77 |
| variable costs +10% | 69 | 76 |
| $CO_2$ transportation costs +10% | 69 | 76 |
| doubled $CO_2$ transport emissions | 69 | 76 |
| CCS-CF at 60% | 82 | 91 |
| EOR net revenues (10$) | 44 | 57 |
| increased storage leakage (0.01% p.a.) | 69 | 76 |
| increased storage leakage (0.1% p.a.) | 70 | 77 |
| increased storage leakage (0.1% p.a., 100a) | 79 | 85 |

Table 4: CCRs taking variation in input parameters into account

# D Inter-technological comparison

| Renewable energy source | Replacement of coal fired plant | Replacement of gas fired plant |
|---|---|---|
| photovoltaics<br>$0.09\,tCO_{2eq}/MWh$ / $264\ \$/MWh$ | $270\ \$/tCO_{2eq}$ | $490\ \$/tCO_{2eq}$ |
| wind energy<br>$0.025\,tCO_{2eq}/MWh$ / $77\ \$/MWh$ | $42\ \$/tCO_{2eq}$ | $25\ \$/tCO_{2eq}$ |
| geothermal energy<br>$0.17\,tCO_{2eq}/MWh$ / $77\ \$/MWh$ | $50\ \$/tCO_{2eq}$ | $36\ \$/tCO_{2eq}$ |
| hydro energy<br>$0.04\,tCO_{2eq}/MWh$ / $55\ \$/MWh$ | $20\ \$/tCO_{2eq}$ | no avoidance costs |

Table 5: Replacement of fossil fired plants by renewables

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