# Perspectives of CCS power plants under different climate policy regimes in Europe

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## 1 Introduction

In the next two decades capacity investments in Europe of about 200 - 400 GW are necessary to compensate decommissioning capacities and to satisfy growing electricity demand. The political framework as well as energy market conditions have significant influence on this investment decisions. In this regard the climate protection targets of the European Commission, aiming the stabilization of the $CO_2$ concentration in the atmosphere at 450 ppm [European Commission, 2007], represent a fundamental criterion for the commissioning of new power plants in the European energy sector. The competitiveness of traditional fossil fuels depends heavily on new technological solutions with reduced carbon emissions. For electricity generation, power plants with carbon capture and storage (CCS) are a widely discussed option. The target of this work is to analyse capture economics of CCS power plants and their contribution to green house gas (GHG) reduction in the European energy system under climate policy conditions. The analysis will be conducted with the Pan-European TIMES energy system model (TIMES PanEU).

## 2 Energy System Model TIMES PanEU

TIMES PanEU is a bottom-up optimisation model of 30 regions which contains all countries of the EU-27 as well as Switzerland (CH), Norway (NO) and Iceland (IS). The objective function of the model is a minimization of the total discounted system costs over the time horizon of 2000 to 2050. A perfect competition among different technologies and paths of energy conversion are assumed in the model. The TIMES PanEU model covers on country level all sectors connected to energy supply and demand for example supply of resources, public and industrial generation of electricity and heat and the sectors industry, commercial, households and transport. Both

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GHG emissions ($CO_2$, $CH_4$, $N_2O$) and also pollutant emissions (CO, $NO_x$, $SO_2$, NMVOC, $PM_{10}$, $PM_{2.5}$) are covered by the model. Due to its high degree of detailing, TIMES PanEU considers country specific particularities, e. g. national carbon storage cost potential curves and country specific renewable potentials. TIMES PanEU is a technology oriented model and contains a comprehensive database which covers a plenty of GHG mitigation technologies of all sectors of the energy system, posing a valid basis for this analysis.

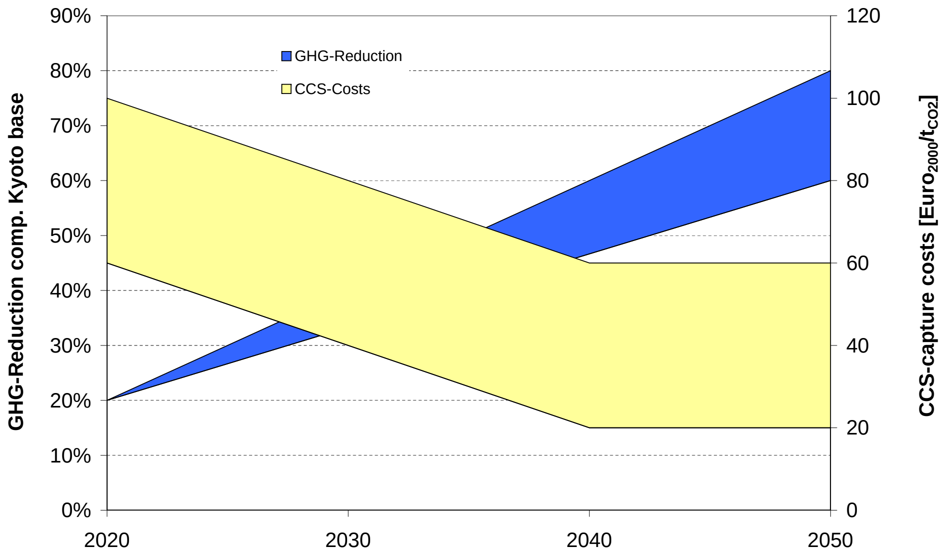
## 3 Scope of the Analysis

Climate policy plays an important role in the European energy policy. The European Commission states the GHG target of a reduction of 20% until 2020 compared to Kyoto base [European Commission, 2008]. However, there is no binding GHG reduction target for European installations for the period beyond 2020 to reach the longterm 450 ppm target. For the realisation of GHG reductions various technological options seam to be feasible which all compete in the liberalized European energy market. Competition arises both at intra and inter-sectoral level. Energy demand side measures represent viable reduction opportunities as well as low and zero carbon energy production technologies. This study aims at analysing the contribution of CCS power plants as a carbon reduced electricity production option in the energy system.

Depending on the GHG reduction target and the resulting carbon prices, CCS power plants face different competition situations towards the alternative reduction measures. Reasons for varying GHG mitigation targets for Europe can result from different usage of the flexible Kyoto mechanisms CDM and JI and the regional specifications of the agreements on world wide emission reductions. To reflect ambiguous European climate policy, the analysis considers not a single GHG reduction path but a variation of GHG targets for 2050. Starting with minus 20% in 2020 a GHG reduction range between 60% and 80% in 2050 compared to Kyoto base will be analysed (figure 1). For a successful competition of CCS power plants on the energy market the adoption of the capture cost performance is required to gain significant market share. For the scope of this study CCS power plant requirements are reduced and expressed as carbon capture costs (including compression at power plant). Depending on efficiency losses and investment penalties compared to power plants without capture, a range of costs for capture is defined for which the perspectives of CCS technologies and main effects of changes in the energy system are analysed. The range of capture costs of CCS power plants is based on a literature study. Capture costs at

CCS power plants are assumed to amount between 60 €$_{2000}$/t$_{CO2}$ and 100 €$_{2000}$/t$_{CO2}$ in 2020 and reaching 20 €$_{2000}$/t$_{CO2}$ to 60 €$_{2000}$/t$_{CO2}$ in 2040 and being constant until 2050 (figure 1).

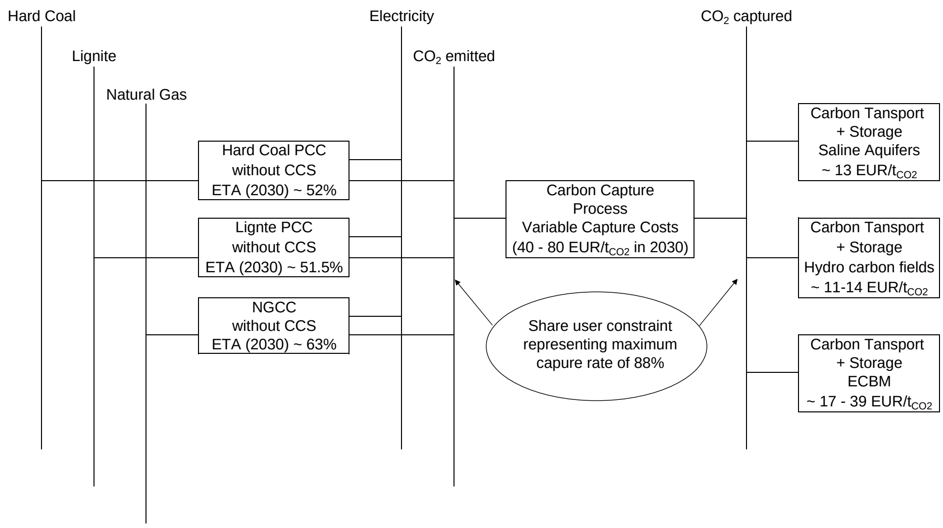
**Figure 1:** Scope of the analysis




For the modeling of varying CCS costs a fuel independent capture process is implemented in TIMES PanEU (figure 2). This process consumes the carbon emissions of the various electricity generation technologies and transfers the consumed carbon dioxide into the commodity "captured $CO_2$", which afterwards flows into the combined process for $CO_2$ transport and storage. To reflect the condition, that CCS power plants can not capture 100% of the $CO_2$ a restriction of a maximum capure rate of 88% is applied. This kind of CCS modeling allows the separate variation of capture costs in the desired range regardless the type of CCS technology and fuel.

For the analysis of the capture costs of CCS power plants the parametric programming routine has been applied to the TIMES PanEU model. Parametric programming represents an advanced analysis of the effects of input parameter variations regarding the model solution. Conversely to sensitivity analysis in linear programming, which aims at analysing marginal changes of input data to the model results, parametric programming allows a variation of input parameters over broad data ranges. In the sensitivity analysis

**Figure 2:** Modeling of the fuel independent CCS process in TIMES PanEU model




the stability interval of the variables of the current solution is determined. The parametric programming routine additionally solves the boundary point problem for the calculation of the optimal partition in the next interval with a further optimisation step. Thus, the parametric programming is a viable method for the assessment of green house gas mitigation options as well as for the analysis of techno-economical requirements of advanced power plants.

# 4 Analysis of CCS technologies under climate policies

This section describes the results of the analysis, emphasising the effects of the variation of capture costs of CCS power plants under different climate policy regimes for the countries of the EU-27 plus Switzerland, Norway and Iceland. The analysis is divided into two sections. The first section describes the changes and effects concerning carbon emissions and quantities of carbon captured and the second section describes the effects in the public electricity sector.

## 4.1 Carbon emissions and carbon captured

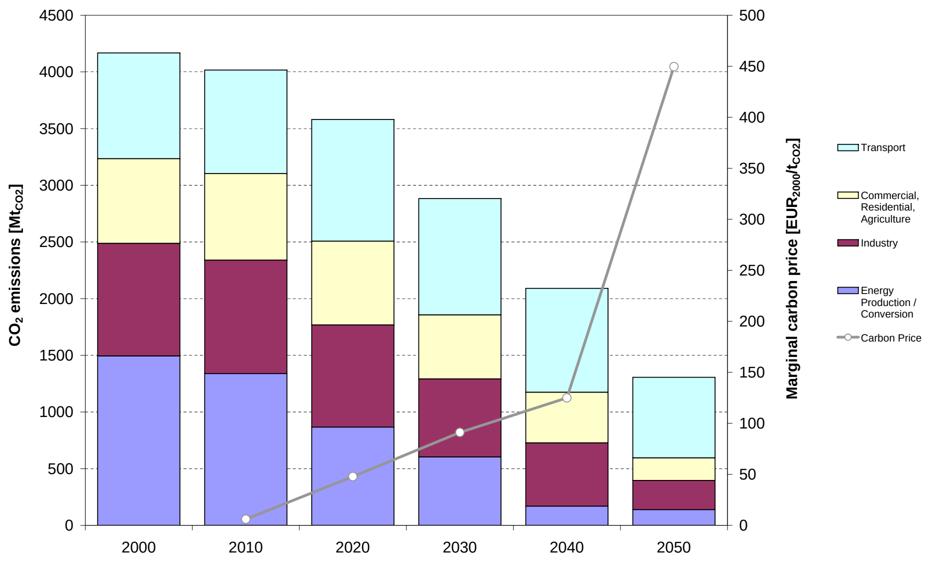
As a starting point for the analysis of the effects of the varying CCS costs, the development of the carbon emissions of the EU-27 plus CH, NO and IS over the model time for a specific carbon reduction path and fixed CCS costs are briefly discussed. Therefore the GHG reduction path of 71% until 2050 compared to Kyoto base for the EU-27 is chosen, which represents the the necessary reduction quantity to meet the 450 ppm target set by the European Commission [Russ u. a., 2007]. For the costs of carbon capture at power plants the upper value (100 €$_{2000}$/t$_{CO2}$ in 2020 declining to 60 €$_{2000}$/t$_{CO2}$ in 2040) of the described range is assumed.

The development of the carbon emissions of the EU-27 plus CH, NO, and IS is characterized by a decline from 2000 of 4.2 Gt to 1.3 Gt in 2050 (figure 3). In the first two decades main emission reductions are realised in the public energy sector, in which 42% of the carbon emissions are reduced between 2000 and 2020. In this time frame the emissions of the industry sector decline by 9% and of the residential, commercial and agricultural sector by 1%. The emissions of the transport sector increase until 2020 by 15% compared to 2000. Beginning in 2030, the industrial sector as well as the residential, commercial and agricultural sector increase their contribution to carbon emission reduction. Of the 700 Mt$_{CO2}$ to be reduced between 2020 an 2030 the industry sector holds a share of 31% and the residential, commercial and agriculture sector 25% respectively. Equal to the periods before, the main reductions come from the public energy sector. This situation remains in 2040, whereas CCS technologies gain importance for the reductions in the public and industrial sectors with almost 700 Mt$_{CO2}$ captured. In 2050 the quantity of carbon captured increases significantly to 1100 Mt$_{CO2}$ but emissions in the public energy production and conversion sector decreases slightly. The reason for this effect is the shifting in the end use sectors towards electrical applications resulting in increased electricity production at low carbon emissions in the public sector. Thus main emission reductions in 2050 are realised in the end use sectors and not in the public energy production. The reduction compared to 2040 is 38% industry related, 31% from residential, commercial and bagriculture and 26% from the transport sector.

Since the study aims at analysing different GHG reduction paths and not only a single one, the following part deals with the question: "How do carbon emissions and capture of carbon dioxide change under different climate targets?". Therefore five GHG paths are introduced, whereas costs of carbon capture are assumed to be constant at high CCS costs (100 €$_{2000}$/t$_{CO2}$ in 2020 decling to 60 €$_{2000}$/t$_{CO2}$ in 2040).

The five European wide GHG reduction paths are analysed in this study,

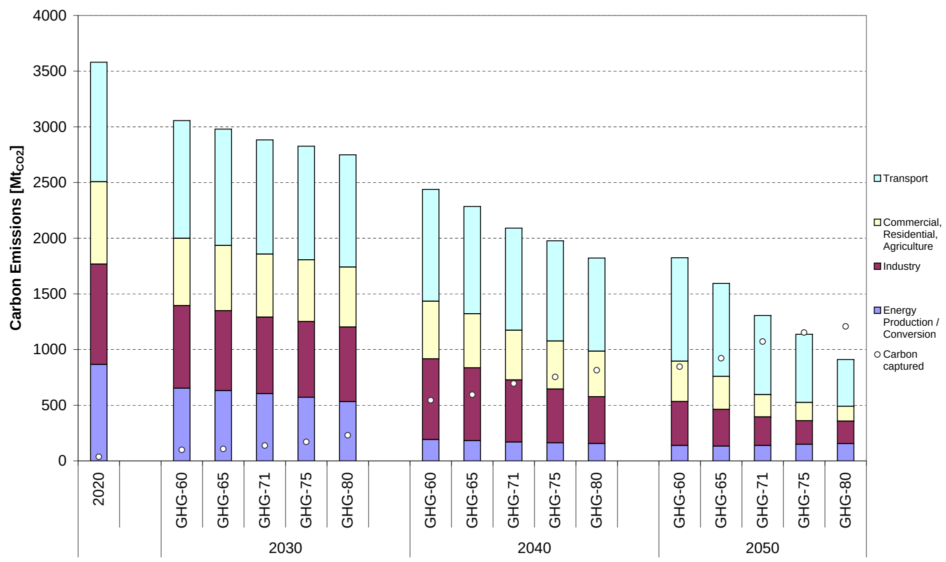
**Figure 3:** $CO_2$ Emissions EU-27 plus CH, NO and IS by sector in 450 ppm case at high carbon capture costs




covering the range of a reduction between 60% and 80% in 2050 compared to Kyoto base and which are named according to their target in 2050 (compare figure 4: GHG-60, GHG-65, GHG-71, GHG-75 and GHG-80). Starting with 3580 $Mt_{CO2}$ in 2020, which corresponds to the -20% GHG target of the European Commission, the carbon emissions decrease to 1824 $Mt_{CO2}$ in 2050 in the GHG-60 path and 910 $Mt_{CO2}$ in the GHG-80 path. Thus in 2050 about 900 Mt of carbon have to be avoided additionally to reach the 80% target compared to the 60% target. Depending on the avoidance costs, sector contribution to additional emission reductions differs between reduction paths and periods. In 2030 the public sector and the industry have most emission reduction potential and contribute with about 60% to total reduction to reach the stronger climate targets. The transport sector has few low cost reduction opportunities and holds the smallest share of total $CO_2$ reduction with 16%. In 2040 the climate target even in the 60% reduction path forces the public sector to realise significant carbon reductions compared to 2030. Consequently a further reduction of the climate target in 2040 from 60% to 80% leads to few additional emission reductions in the public sector (34 $Mt_{CO2}$ in 2040). Almost half of the carbon emissions to be avoided are reduced in the industry sector (305 $Mt_{CO2}$ in 2040 from GHG-60 path to GHG-80 path). The transport sector and residential, commercial and agriculture reduce the remaining 277 $Mt_{CO2}$ to reach the 80% GHG target. In 2050 the sector composition shifts towards the residential, commercial and agricultural sector and the transport sector, which in total reduce 743 $Mt_{CO2}$ for the transition from GHG-60 to GHG-80 path and thus bear about 80% of the reduction effort.

The quantities of carbon captured increases with tightening carbon reduction (figure 4). In 2030 99 $Mt_{CO2}$ are captured in the GHG-60 path and 230 $Mt_{CO2}$ under a strong climate target (GHG-80 path). This increase by 130% represents a high sensitivity of the carbon capture regarding climate targets. In the following periods the sensitivity declines at comparably higher quantities of carbon captured. In 2040 CCS technologies capture 544 $Mt_{CO2}$ under less ambitious climate targets (GHG-60 path) and 814 $Mt_{CO2}$ under the 80% climate policy regime, which increases in 2050 to 846 $Mt_{CO2}$ (GHG-60) and 1208 $Mt_{CO2}$ (GHG-80) respectively).

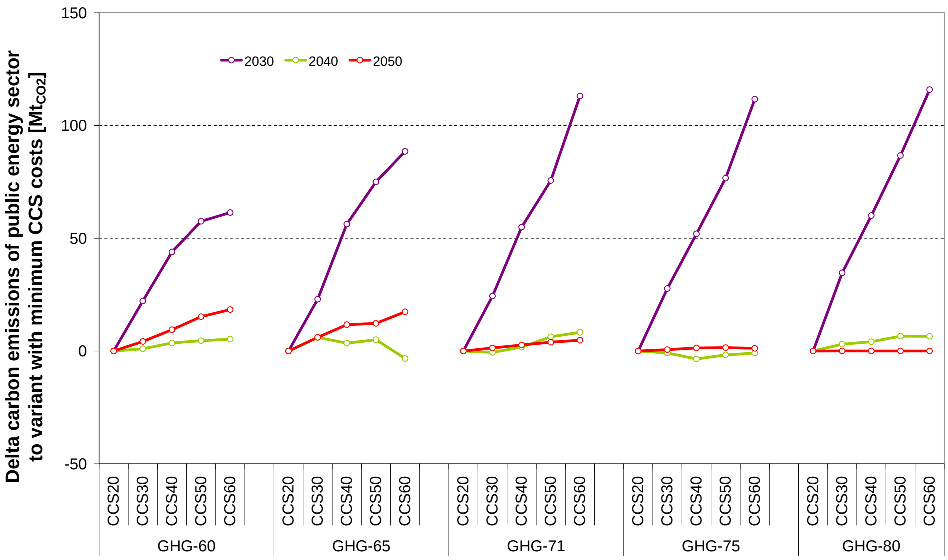
**Figure 4:** $CO_2$ Emissions of the EU-27 plus CH, NO and IS by sector under different climate paths for the case of high carbon capture costs




For the analysis of the effects of different costs of carbon capture and the resulting impact of CCS technologies in the energy system, additional to the five GHG paths a variation of the CCS costs is introduced in the following. For the description of the results, five CCS cost variations will be discussed.

They are named similar to GHG path naming, representing the capture costs reached in 2040 (CCS20, CCS30, CCS40, CCS50 and CCS60).
The results of the development of the carbon emissions in the public energy sector are displayed as difference of the CCS cost variations (CCS30, CCS40, CCS50, CCS60) to the least cost CCS option (CCS20) for each GHG path (see figure 5). The figure underlines the previously mentioned effect of a high sensitivity of CCS capture in the period 2030. In the GHG path with a relatively modest GHG target (GHG-60) a reduction of capture costs from 80 €$_{2000}$/t$_{CO2}$ (CCS60)[2] to 40 €$_{2000}$/t$_{CO2}$ (CCS20) can lead to a decrease of carbon emission from public energy production by 61 Mt$_{CO2}$ in 2030 and in the GHG-65 path 89 Mt$_{CO2}$. Under a policy regime aiming a GHG reduction of 71% or more the reduction of CCS capture costs to 40 €$_{2000}$/t$_{CO2}$ can even reduce carbon emissions in the public energy sector by about 115 Mt$_{CO2}$ in 2030.

**Figure 5:** Difference of $CO_2$ Emissions of the EU-27 plus CH, NO and IS of all end use sectors compared to the variant with minimum CCS costs for the different climate paths

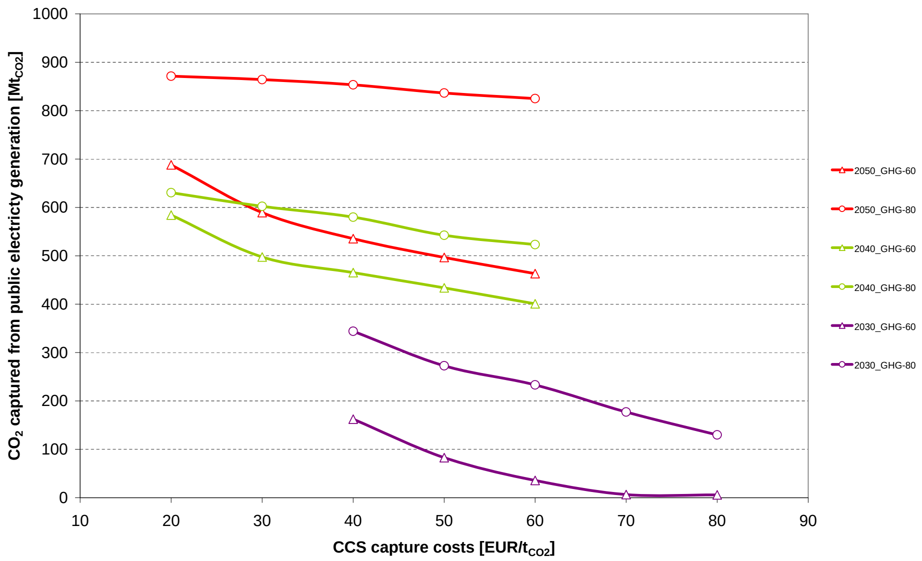



In the periods 2040 and 2050 carbon emissions in the public energy sec-

[2] According to the definition of the decrease of CCS costs over time, the range of varying CCS costs covers 40 €$_{2000}$/t$_{CO2}$ (CCS20) to 80 €$_{2000}$/t$_{CO2}$ (CCS60) in 2030 (compare figure 1).

tor are less sensitive to changes of CCS capture costs compared to 2030. Decreases f capture costs cause carbon emission reductions of maximum 18 $Mt_{CO2}$. In these periods the public energy sector already produces at low carbon emissions independent from CCS costs. For GHG-60 path and GHG-65 path the total carbon emission from public energy sector are more sensitive to CCS cost changes than in 2040 , since there is a higher flexibility in these paths in 2050 concerning the GHG reduction option than in 2040 or under more restrictive climate policy. Under certain conditions declining capture costs lead to an increase of carbon emissions in the public energy sector. The reason of this effect is the increase of electricity demand due to lower capture prices and consequently lower electricity prices, which results to a shift of carbon emissions from the public sector to end use sectors. But these effects are comparably small and can be neglected for the scope of this analysis. Under a strong climate target (GHG-80) CCS costs variation between 20 $€_{2000}/t_{CO2}$ and 60 $€_{2000}/t_{CO2}$ play a subordinated role for the total carbon emissions of the public power sector since a high level of electricity production, accompanied by a minimum of carbon emissions from electricity generation is reached.

**Figure 6:** Carbon capture of the EU-27 plus CH, NO and IS from public electricity production depending on the cost of capture for lowest and highest climate target levels



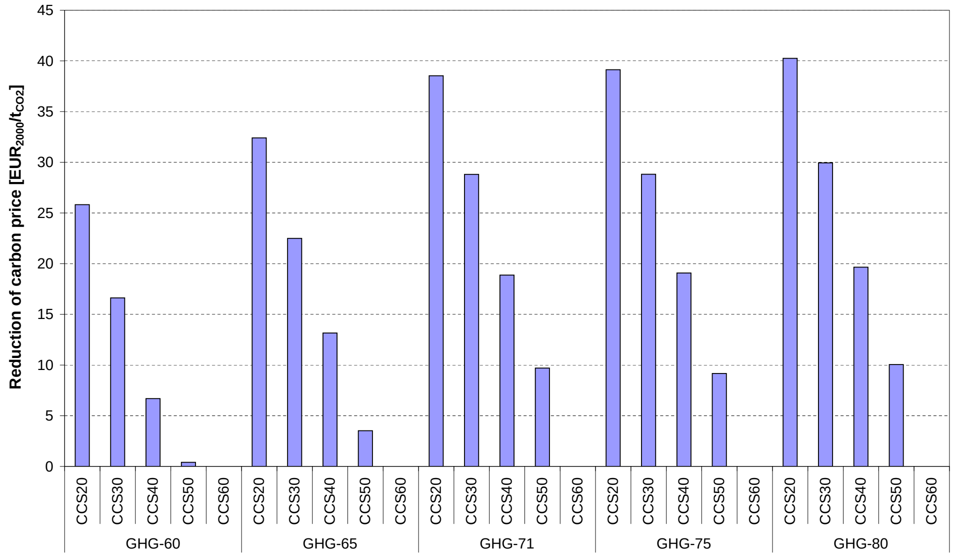
Regarding at the carbon captured by technologies of the public energy sector (illustrated in figure 6 for the lower path GHG-60 and the upper path GHG-80 for 2030, 2040 and 2050) a high sensitivity in the year 2030 can be observed as well. In 2030 the quantity of captured $CO_2$ varies from almost zero in the GHG-60 path at capture costs of 70 $€_{2000}/t_{CO2}$ up to a maximum of 344 $Mt_{CO2}$ in the GHG-80 path with least cost CCS option. Comparing the upper and lower GHG path for the year 2030 it can be stated, that capture level of GHG-80 path at high capture costs is reached in GHG-60 path only with CCS cost savings of about 35 $€_{2000}/t_{CO2}$. Comparing the upper and the lower GHG path for the CCS low cost option in 2030, additional 182 $Mt_{CO2}$ are captured due to the tighter climate target. However cost reduction of carbon capture from 70 $€_{2000}/t_{CO2}$ to 30 $€_{2000}/t_{CO2}$ under the GHG-80 path has higher impact on additional capture quantities with 214 $Mt_{CO2}$ in 2030 than tightening the climate target.

According to the effects discussed above, the different climate targets and capture costs cause changes of the carbon price. Most influence of the carbon price can be observed in 2030, due to the high sensitivity and changes of the emissions of the public energy sector into end use sectors in case of increasing carbon capture costs. In general the carbon price in 2030 varies between 52 $€_{2000}/t_{CO2}$ under modest climate targets for the CCS least cost option up to 92 $€_{2000}/t_{CO2}$ for strong climate targets and high capture costs. Considering the costs for transport and carbon storage and the corresponding capture costs, the carbon prices equal to the costs of the CCS chain, meaning that CCS technologies determine the carbon price directly as the marginal abatement technology in 2030. This statement is approved by figure 7 which shows that the reduction of carbon prices in 2030 compared to the CCS least cost option is more or less equal to difference of the capture costs.

## 4.2 Implications of different climate policy regimes and varying CCS costs for the public electricity sector

It can be expected, that different climate regimes and costs of carbon capture imply changes of the electricity generation. However in 2030 neither changes of the climate target nor the costs of carbon capture lead to significant changes of the total electricity generation (figure 8). The level of electricity generated remains comparably stable at about 3400 TWh. In contrast, production quantities in 2040 vary from about 3600 TWh in the GHG-60 path to about 3800 TWh in the GHG-80 path, with a maximum increase of 7% due to stronger climate restrictions. Within the climate paths a maximum increase of electricity generation of 3.5% can be gained by the reduction of carbon capture costs.

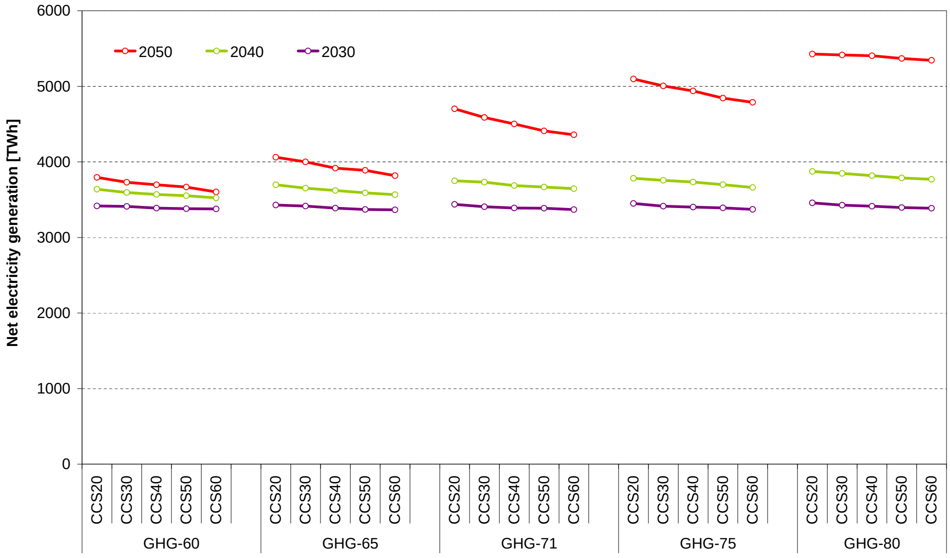
**Figure 7:** Difference of carbon prices compared to least cost CCS option for the year 2030




In 2050 these effects are much more evident. In the GHG-60 path electricity generation in 2050 varies between 3600 TWh (CCS60) and 3800 TWh (CCS20) and for GHG-80 path 5340 TWh (CCS60) and 5430 TWh (CCS20), representing an maximum increase from GHG-60 to GHG-80 of 48% in the CCS60 variant. This underlines the effect, that under increasing climate targets, end use sectors switch to electricity applications, preconditioning a low carbon generation. For the climate paths GHG-71 and GHG-75 total electricity generation varies under changing CCS costs. In GHG-71 path in 2050 the increase of capture costs from 20 $€_{2000}/\text{t}_{CO2}$ to 60 $€_{2000}/\text{t}_{CO2}$ leads to a reduction of total generation of 7.3%. Under the most restrictive climate path (GHG-80) electricity generation in 2050 is nearly insensitive to the CCS cost variation analysed in this study.

The composition of fuels used for electricity generation in 2030, shows a high share of natural gas (minimum 30%) and stable shares of nuclear of about 25% of net generation and of hydro of about 16% over all GHG paths and CCS costs variants. Changes due to different GHG paths and CCS costs primary concern use of coal, natural gas and renewable energies (figure 9). The figure displays the changes of the CCS cost variations to the

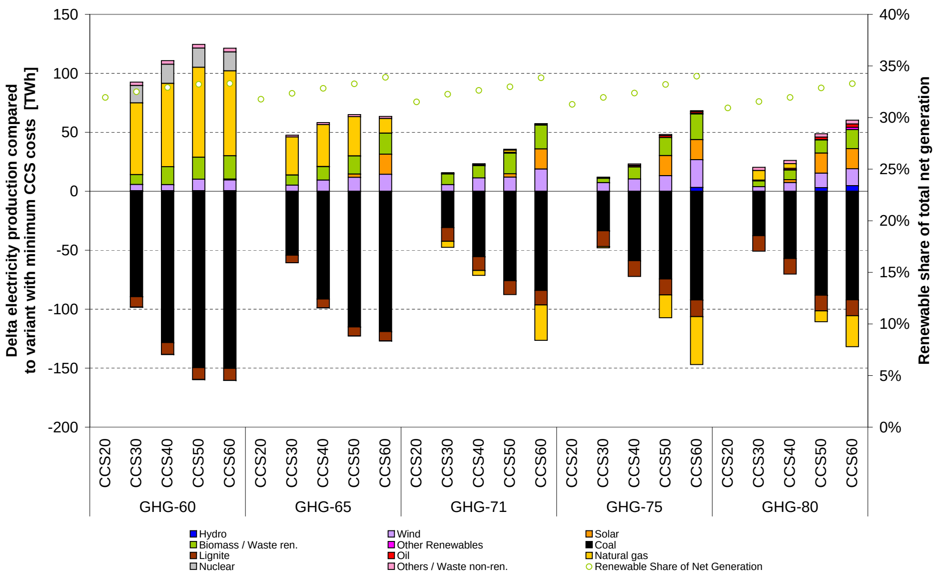
**Figure 8:** Net electricity generation in the EU-27 plus CH, NO and IS for the periods 2030, 2040, 2050 depending on climate target and CCS costs




least cost options of each GHG path. Since in 2030 few CCS technologies are used under moderate climate targets (GHG-60 and GHG-65), the increase of CCS costs leads to a substitution of hard coal by natural gas and renewable energies. Under GHG-60 path the coal based electricity generation of the CCS least cost variant exceeds the variant with the highest CCS costs by 160 TWh but consequently electricity from natural gas is in the CCS20 variant 72 TWh lower and electricity from renewables 30 TWh. The share of renewables of total net generation increases under GHG-60 path from the CCS20 variant of 32% to 33% in the CCS60 variant.
For the GHG paths with a reduction target higher than 65% fossils are mainly substituted by renewable energies. The highest effects occur in the GHG-75 path in which the fossil generation in 2030 reduces by 147 TWh due to increase of CCS costs from 40 $€_{2000}/t_{CO2}$ (CCS20) to 80 $€_{2000}/t_{CO2}$ (CCS60) and the renewable generation increases by 66 TWh respectively. In the GHG-75 path the share of renewables of net generation amounts to minimum 31% in the CCS20 variant and maximum 34% in the CCS60 variant.

In 2050 the electricity generation is dominated by natural gas and nuclear power plants, which produce together more than half of the electricity independent from the GHG path and CCS costs. Changes of the fuel mix

**Figure 9:** Electricity generation in the EU-27 plus CH, NO and IS in 2030 compared to the variant with minimum CCS costs for the different climate paths




for electricity generation primary concern coal, natural gas and renewable energies (figure 10). Under the GHG-60 path primary coal based electricity decreases with rising capture costs in 2050. In the CCS variant with 20 €$_{2000}$/t$_{CO2}$ capture costs additional 261 TWh electricity from coal power plants are generated compared to the variant with 60 €$_{2000}$/t$_{CO2}$. Substitution effects from coal to natural gas as observed in GHG-60 in period 2030 play a subordinated role in 2050.

Under a moderate climate target in 2050 156 TWh of electricity coming from renewable energies is replaced by CCS power plants if the capture costs can be reduced from 60 €$_{2000}$/t$_{CO2}$ to 20 €$_{2000}$/t$_{CO2}$. This means a decrease of the share of renewables of total generation from 39% in the CCS60 variant to 33% in the CCS20 variant in the GHG60 path. The share of renewables displaced by CCS technologies declines with tightening the climate target and reduces to a minimum of 43 TWh under the GHG-80 path in 2050. The share of renewables of electricity generation increases with relaxing the climate target due to the reduction of total electricity generation under less ambitious targets.

**Figure 10:** Electricity generation in the EU-27 plus CH, NO and IS in 2050 compared to the variant with minimum CCS costs for the different climate paths

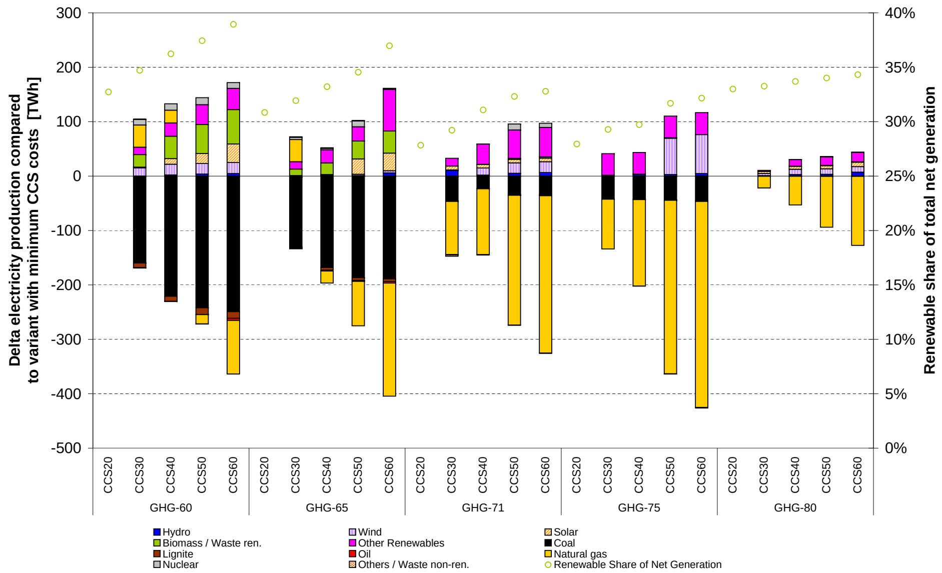



Figure 10 shows, that in 2050 especially in the GHG-71 path and the GHG-75 path natural gas based electricity is less substituted but primary saved due to a reduction of electricity demand. This corresponds to the conclusions derived from figure 5.

## 5 Conclusion

The analyse of the perspectives of CCS power plants in Europe under different climate regimes with the Pan-European TIMES model showed, that the contribution of CCS power plants to emission reduction in 2030 an thus their market shares depend heavily on the cost performance. In the public energy sector capture quantities between zero and 350 $Mt_{CO2}$ can be observed in 2030. In this period possible cost reductions can have more impact on CCS deployment than the tightness of the climate policy target. The total electricity generated is not expected to change significantly but the composition of fuels for production. Under high CCS costs coal based electricity switches to generation from natural gas, especially under lower GHG targets. In 2040 carbon quantities between 400 $Mt_{CO2}$ and 630 $Mt_{CO2}$ could be captured, depending on the political framework and capture costs, whereas the capture quantities in 2040 are less sensitive to climate policy targets than to CCS costs. In 2050 an amount of 460 $Mt_{CO2}$ to 870 $Mt_{CO2}$ of carbon dioxide could be captured, whereas the use of CCS technologies is primary determined by the obligations set by climate policy. Under an ambitious climate policy (-80% in 2050 compared to Kyoto base), CCS cost decreases play a subordinated role for the use of CCS technologies in 2050. Under less ambitious climate policy regimes enhancement of the CCS cost performance leads to an increased electricity generation as well as to substitution effects from natural gas to renewables (about 150 TWh) and under moderate climate targets from coal to renewables (about 150 TWh).

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