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**Institute for Future Energy Consumer Needs and Behavior (FCN)**

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# Impact of CCS on the economics of coal-fired power plants: Why investment costs do and efficiency doesn't matter

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**Abstract**

In this paper we analyze how development of the economics related to CCS technology in coal-fired power plants affects market diffusion. Specifically, we (1) show the (significant) variance in economic expectations for commercial-grade CCS hard coal power plants observed in selected recent scientific publications; (2) analyze the impact of economic factors related to CCS on electricity generation costs; and (3) study possible deployment of CCS technology in Europe using the bottom-up electricity sector model HECTOR. Simulation results show that investment costs strongly influence the market deployment of coal-fired CCS power plants, leading to a share of 16% in European generation capacity by 2025 with the lowest observed investment costs of 1400 €/kW, but only 2% with the highest of 3000 €/kW. A variation of conversion efficiency between 37% and 44%, the minimum and maximum observed values, only leads to a share of CCS-equipped power plants between 13 and 15%. These findings are robust for the Base Case with a $CO_2$ price of 43 €/t and also for sensitivities with 30 and 20 €/t $CO_2$, but with a lower effect, as the overall share of CCS is significantly reduced at these prices.

*Key words:* Electricity market, simulation, model, CCS, power plant economics, technology adoption
*JEL classification:* O33, Q47

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## 1. Introduction

Stabilization of the atmospheric carbon dioxide ($CO_2$) concentration will be one of the prime challenges for the energy sector in the upcoming decades. Starting with the Kyoto Protocol in 1997, the world's economies have consequently introduced instruments to limit $CO_2$ emissions, such as the European Union's Emissions Trading Scheme (ETS). The main contributor to anthropogenic $CO_2$ emissions is the combustion of fossil fuels, which has been a major contributor to our wealth and standard of living since the early days of industrialization. Coal alone accounts for some 70% of Europe's $CO_2$ emissions from power generation (EU COMMISSION, 2006). Given GHG reductions, such as the existing -20% target in Europe (EU COMMISSION, 2007) or the expected -17% target in the U.S. (US CONGRESS, 2009), the future and economics of coal-fired power plants are quite unclear. Yet, in the short and medium term, we will still need them, because alternative renewable energy sources, like wind or solar power, depend on certain wind speeds or solar irradiation.

Carbon capture and storage (CCS) is widely seen as a major opportunity to continue fossil fuel-based generation while contributing to $CO_2$ abatement. About half of the world's annual $CO_2$ emissions, 14 Gt, are from large point sources and therefore addressable through CCS (IEA, 2003). The International Energy Agency (IEA) predicts 160 GW of worldwide CCS coal capacity in operation by 2030, even in a conservative 550 ppm $CO_2e$[1] scenario (IEA 2008). Currently, eight carbon sequestration sites are in operation (SCIENCE, 2009), and over 20 CCS power plants are planned worldwide (WYNN, 2008).

Deployment of this technology depends on a variety of success factors, such as industrial availability of capture technology (IPCC, 2005; MIT, 2007), sufficiently high $CO_2$ prices or reduction targets (WISE and DOOLEY, 2009), learning curve effects (RIAHI ET AL., 2004; ABRELL ET AL., 2009), leakage-free and affordable storage and infrastructure (ODENBERGER ET AL., 2008; DAMEN ET AL., 2009), fossil fuel prices (MARTINSEN ET AL., 2007; JOHNSON and KEITH, 2004), and favorable CCS regulation (GROENENBERG and DE CONINCK, 2008). Whereas the literature available so far provides a good overview of CCS deployment in the light of these success factors, we still know relatively little about how economic development

[1] $CO_2$-equivalents ($CO_2e$) also include $N_2O$, $CH_4$ and synthetic gases like Perfluorocarbons (PFC), Hydrofluorocarbons (HFC), and sulfur hexafluoride ($SF_6$). These gases are, based on the level at which they reflect heat, weighted higher than $CO_2$.

related to CCS technology affects its market diffusion. This is the focus of the research presented in this article. Specifically, in section 2 we show the (significant) variation in economic expectations for CCS hard coal power plants observed in selected recent publications. In section 3 we analyze the impact of economic factors related to CCS on electricity generation costs. In section 4 we study possible deployment of CCS technology in Europe until 2040 using the novel bottom-up electricity model HECTOR (LOHWASSER and MADLENER, 2009), and section 5 concludes.

## 2. Expectations on the economics of coal-fired CCS power plants

For our analysis, we first screened eight key references on CCS, providing 12 data sets for the economics of CCS power plants. Specifically, these are IPCC (2005); MIT (2007); JOHNSON and KEITH (2004); MARTINSEN ET AL. (2007); ODENBERGER ET AL. (2008); DAMEN ET AL. (2008); MCKINSEY (2008) and WISE and DOOLEY (2009). The first two focus on present costs, i.e. for the current pilot development stage of CCS, shown in Table 1a. The latter six provide assessments for the commercial development phase of CCS expected to commence around 2020, shown in Table 1b. All studies mentioned focus on hard coal-fired plants, i.e. lignite plants are not considered.

As the data points arise from different sources, any underlying limitations must be kept in mind for comparisons. The two sources for present values (Table 1a) all report values for CCS coal-fired plants that are, in their view, representative, but both sources stem from a compilation of eight individual CCS plant design studies that naturally have different technological concepts, operating parameters, cooling methods, plant locations, generation capacities, coal types, capacity factors, etc. The results published by MIT are normalized to a plant size of 500 MW and to Illinois #6 bituminous coal, using Carnegie Mellon's IECM model, and imply that the remaining factors could cause differences in (conversion) efficiency of about 2-3%. The IPCC, on the other hand, does not normalize for plant size or coal types, but publishes "representative mean values" instead. The ranges for their plant sizes considered are 450-700 MW for pulverized coal (PC) and 350-750 MW for integrated gasification combined cycle (IGCC) plants. All sources use bituminous coal with sulfur contents between 1 and 2.5%. Additionally, the MIT report uses four of its eight sources that have already been used by the IPCC report and, therefore, show up twice in Table 1a, once with and once without normalization.

**Table 1: Studies on economics of coal-fired power plants with CCS**
(a) Current economics (pilot phase)

| Source / Lead author | **Averages** | IPCC | | MIT [c] | |
|---|---|---|---|---|---|
| Year of publication | 2006 | 2005 | | 2007 | |
| Figures from year | 2002 | 2000-2004 | | 2000-2004 | |
| Figures for year | 2005 | 2005 | 2005 | 2005 | 2005 |
| Plant type | Both | PC | IGCC | PC | IGCC |
| Investment cost (€/kW$_{el}$) | 1829 | 1941 [a] | 1690 [a] | 1935 [a] | 1750 [a] |
| Conv. efficiency (Net, LHV) | 34.0% | 33.0% | 35.0% | 35.5% [d] | 32.5% [d] |
| Technical lifetime (years) | n/a | n/a | | n/a | |
| $CO_2$-Capture ratio | 89.2% | 88.5% [b] | 88.2% [b] | 90.0% | 90.0% |
| Fixed O&M (€/kW$_{el}$/year) | 77.6 | n/a | | 79.1 [a,e] | 51.9 [a,e] |
| Var O&M (€/MWh) | 1.8 | n/a | | 1.9 [a,e] | 1.2 [a,e] |

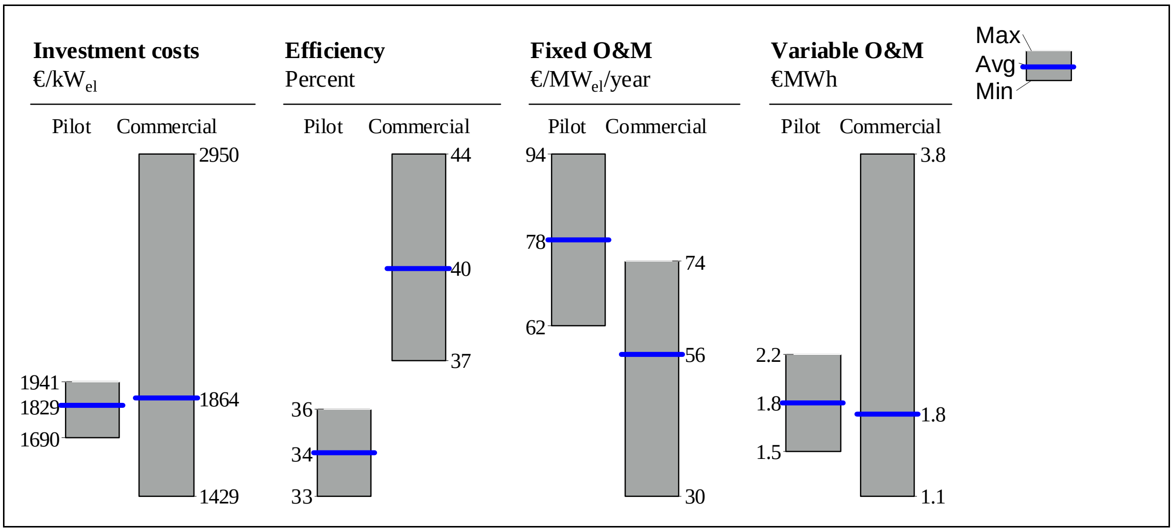
(b) Expected future economics (commercial phase)

| Source / Lead author | **Averages** | Johnson | Martinsen | | Odenberger | Damen | | McKinsey | Wise |
|---|---|---|---|---|---|---|---|---|---|
| Year of publication | 2007 | 2004 | 2007 | | 2008 | 2008 | | 2008 | 2009 |
| Figures from year | 2004 | 2001 | 2004 | | 2006 | 2004-2006 | | 2008 | 2000 |
| Figures for year | 2018 | 2015 | 2020 | 2020 | 2020 | 2020 | 2020 | 2020 | 2012 |
| Plant type | Both | IGCC | PC | IGCC | PC | PC | IGCC | Mix | IGCC |
| Investment cost (€/kW$_{el}$) | 1864 | 2065 [a] | 1750 | 1900 | 1614 | 1600 | 1600 | 2950 | 1429 [a,f] |
| Conv. efficiency (Net, LHV) | 40.4% | 37.5% [d] | 37.4% | 44.3% | 37.2% | 40.0% | 43.0% | 40.0% | 43.5% |
| Technical lifetime (years) | 42.5 | n/a | n/a | | 40 | 45 | 45 | 40 | n/a |
| $CO_2$-Capture ratio | 90.3% | n/a | n/a | | n/a | 90.0% | 90.0% | 91.0% | 90.0% |
| Fixed O&M (€/kW$_{el}$/year) | 56.3 | 59.8 [a] | n/a | | 29.7 | 68.0 [e] | 54.4 [e] | 73.8 | 52.1 [a,e,f] |
| Var O&M (€/MWh) | 1.8 | 3.8 [a] | n/a | | 1.1 | 1.6 [e] | 1.3 [e] | 1.5 | 1.2 [a,e,f] |

[a] Currency US$ converted to € with average exchange rate of the originating year(s)
[b] Converted from emissions increase per MWh to capture ratio of $CO_2$
[c] Uses 4 of its 8 sources from the IPCC report, but normalizes them with a model
[d] Higher heating value (HHV) converted to lower heating value (LHV) with LHV/HHV of coal = 0.96
[e] O&M costs split into 85% fixed and 15% variable components based on the ratio from McKinsey (2008)
[f] Adjusted with 1.5% inflation to the year 2005 (was 2012)
Plant type PC refers to pulverized coal plants, IGCC to integrated gasification combined cycle plants

The future expectations reported in Table 1b are easier to compare, as they are all used as an input for long-term economic forecast models, and hence represent the (expected) commercial-grade middle values faced by investors. Only the source from MCKINSEY (2008) does not use its data as input to economic models; specifically, they report a commercial-grade "reference case" CCS coal power plant that represents all potential technologies (Pre- and Post Combustion Capture, Oxyfuel) and fuel types (hard coal, lignite) respectively. We have made no adjustments for inflation, as all sources, both for present values and future outlooks, report real prices between 2001 and 2005, with the exception of WISE (2009), where nominal 2012 figures are reported, that we deflated to 2005 with an annual inflation rate of 1.5%. All sources include on-site $CO_2$ compression, but do not include $CO_2$ transport or storage. Also, we report averages spanning both PC and IGCC plants, as the underlying capture technologies are still in an early stage of development. Hence, it is currently not possible to predict which one will be the prime technology in the future. A compilation of the ranges of the reported figures and their averages is reported in Figure 1.

**Figure 1: Current (pilot stage) and expected future (commercial stage) cost and conversion efficiency of coal-fired power plants with CCS**




With these limitations in mind, we see that all future outlooks expect a noticeable increase in conversion efficiency from currently 33-36% to 37-44%, with an average value of 40%. This is not the case for investment costs, as the expected average of our surveyed publications is 1864 €/kW for the commercial development phase, which is about the same value as currently achieved (1829 €/kW). Therefore, we can see that the focus of current research interest is mainly on improving capture process efficiency and less so on improving construction costs. The focus on efficiency is in line with the current objectives of utilities and power plant suppliers, as identified by a survey conducted by ECOFYS (2008). The primary result was that "efficiency [is the] key factor influencing [the] economics of power plants". An outcome of their interviews was also that suppliers base their offers on maximizing fuel efficiency, and one of the suppliers even explicitly highlighted "energy efficiency nearly always pays off".

Average variable operating and maintenance (O&M) costs are expected to remain stable, whereas fixed O&M costs will decrease slightly. However, the significance of this conclusion is limited, as only two considered sources explicitly split between variable and fixed O&M

costs. Plant lifetime is not expected to change significantly through CCS, as the stated values between 40 and 45 years are equal to the current lifetimes of existing coal plants.

When comparing the future expectations with each other, we see a large variation in investment costs, ranging between 1450 and 2950 €/kW, indicating the significant level of uncertainty for this factor. This uncertainty also applies to variable and fixed O&M costs, which range between 1.1 and 3.8 €/MWh for variable and between 30 and 74 €/kW/year for fixed costs. The forecasts on efficiency are narrower, with a range between 37 and 44%. Whereas it is difficult to draw conclusions from these absolute figures, we do see in which ranges the current literature expects the economics of power plants to be. Based on these ranges, we now analyze the economic relevance of every factor's uncertainty.

## 3. Relevance of economic factors for total electricity generation costs

In order to understand the economic relevance of the uncertainty in CCS power plants development, we calculate the total cost of electricity (COE) per MWh generated, based on the averages of all values shown in Table 1b. Hence, a hard-coal fired CCS plant in commercial development stage initially costs 1864 €/kW at an efficiency of 40.4%, with 1.8 €/MWh variable and 56.3 €/kW fixed costs. It has an expected lifetime of 42.5 years and captures 90% of its produced $CO_2$. Its cost of electricity generation, i.e. full costs at which it can recover all costs including depreciation, is 65.9 €/MWh under the assumptions outlined in Table 2. For comparison, under these assumptions, current new hard coal power plants without CCS have a COE of 72.1 €/MWh[2], and natural gas plants one of 64.9 €/MWh[3].

We see that fixed costs make up 45% of total electricity generation costs, a major shift from current new coal plants, that have 23%[2] , and natural gas plants at 16%[3]. This is similar with O&M costs, that make up 15% of the total COE, about three times as much compared to current natural gas and coal plants. This shift of costs from variable to fixed components is effectively a loss of flexibility for these plants, that are, more than traditional coal and natural gas power plants without CCS, dependent on achieving a high utilization.

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[2] Super-critical pulverized coal power plant. Investment costs: 1300 €/kW, efficiency: 45%. Other assumptions as of Table 2.

[3] Combined-cycle natural gas turbine plant (CCGT). Investment costs: 600 €/kW, efficiency: 51% (HHV). Price of natural gas 19.1 €/MWh (historic average 2005-2008 at the TTF hub). Other assumptions as of Table 2.

**Table 2: Costs of electricity for a coal-fired CCS power plant with avg. economics derived from Table 1b**

| Electricity generation costs (in €/MWh) | | Assumptions | Rationale for assumptions |
|---|---|---|---|
| Variable components: | | | |
| Fuel | 26.0 | 90 US$/t coal price,<br>1.37 US$/€ exchange rate | Historic average 2005-2008 at ARA<br>Historic average exchange rate 2005-2008 |
| Variable O&M | 1.8 | | |
| $CO_2$ emissions | 3.3 | 40 €/t $CO_2$ price | DG-TREN (2008), Deutsche Bank (2008) |
| $CO_2$ transport and storage | 4.9 | 3.15 €/t $CO_2$ transport, 3.29 €/t $CO_2$ storage | Averages from sources reported in Table 1b |
| Total variable costs | 36.0 | | |
| Fixed components: | | | |
| Capital | 22.0 | 81% utilization, 8% WACC | Utilization: Averages of sources reported in Table 1b; WACC: authors' estimate |
| Fixed O&M | 8.0 | 81% utilization | |
| Total fixed costs | 30.0 | | |
| **Total COE** | **65.9** | | |

Notes: ARA=Amsterdam Rotterdam Antwerp; COE=Cost of Electricity; WACC=Weighted Average Cost of Capital

Costs for transport and storage at 4.9 €/MWh (6.4 €/t) are low in comparison with fuel costs and capital costs. These figures are based on all sources of Table 1b that reported these figures, namely MARTINSEN et al. (2007), ODENBERGER et al. (2008) and MCKINSEY (2008). These figures include all costs and assume a $CO_2$ pipeline length of 200-300 km. Even if, compared to the $CO_2$ capture technologies, the technological development for transport and storage is a more mature stage, there is yet great uncertainty in this area, covering topics on public acceptance, land vs. sea storage, storage type, and associated pipeline length. This leads to a strong variation within the three sources mentioned earlier, that report values between 0.4 €/t for transport and 1.4 €/t for storage (MARTINSEN et al., 2007) to 4-6 €/t for transport and 4-12 €/t for storage (MCKINSEY, 2008), with ODENBERGER et al. (2008) in between. To limit complexity, we use the average value of all sources for this simulation, thereby also excluding niche-methods such as ship transport, similar to LNG.

In a next step, we now apply partial factor variation to the plant, individually changing one factor while keeping the others constant. This is statistically justifiable as the correlation between the factors is not significant[4]. The minimum and maximum ranges are hereby from the sources in Table 1b, and the corresponding COE with these minimum and maximum

[4] For a dataset with correlated variables, variation of one factor must entail the variation of the correlated factor(s), as they are not independent. The two factors contributing most to the COE, i.e. investment costs and conversion efficiency, are not correlated significantly (correlation -17%).

values is reported in Table 3. Additionally, we highlight the absolute spread between the minimum and maximum values relative to the average value as "economic uncertainty" in order to reflect by how much the uncertainty of each factor impacts the COE.

**Table 3: Outcome of partial factor variation for power plant economics as of Table 2**

| | | Future expectation | | | Corresponding COE | | | Economic uncertainty |
|---|---|---|---|---|---|---|---|---|
| | | Min | Avg | Max | Min | Avg | Max | $(COE_{max}-COE_{min})/COE_{avg}$ |
| Investment costs | €/kW | 1429 | 1864 | 2950 | 60.8 | 65.9 | 78.7 | 27% |
| Conv. efficiency | % | 37.2 | 40.4 | 44.3 | 68.8 | 65.9 | 62.9 | 9% |
| Fixed O&M costs | €/kW | 29.7 | 56.3 | 73.8 | 62.2 | 65.9 | 68.4 | 9% |
| Var. O&M costs | €/MWh | 1.1 | 1.8 | 3.8 | 65.3 | 65.9 | 68.0 | 4% |
| Plant lifetime | Years | 40.0 | 42.5 | 45.0 | 66.1 | 65.9 | 65.8 | 1% |
| $CO_2$ capture ratio | % | 90.0 | 90.3 | 91.0 | 66.0 | 65.9 | 65.7 | 0% |

We see that investment costs are the economically most relevant factor, three times as much as efficiency. This, however, is contrary to the currently existing focus on efficiency, as outlined in the previous section. If the most pessimistic investment costs of 2950 €/kW hold true, the COE of CCS-enabled coal power plants will be beyond regular non-CCS plants, even at the high assumed $CO_2$ price of 40 €/t. Also, fixed O&M costs have a comparably high impact on the COE, as they can change generation costs by up to 4 €/MWh. The remaining factors, namely variable O&M costs, plant lifetime and the $CO_2$ capture ratio, are of lesser importance.

To support trade-off decisions between efficiency and investment costs, we can calculate an isocost curve for the COE calculation of Table 2 to obtain the relationship between efficiency $\eta$ and investment cost $I$ combinations that reach a COE of 65.9 €/MWh. This leads to a quadratic equation of the form:

$$I = -21538 \cdot \eta^2 + 24551 \cdot \eta - 4536 \tag{1}$$

The isocost curve is calculated by solving for all feasible values of efficiency $\eta$ and investment cost $I$ in the COE calculation of Table 2 at a constant COE of 65.9 €/MWh. Given, e.g. a reduction in efficiency, this leads to the required improvement of capital cost needed to achieve the same COE, with all other assumptions held constant.

We see that efforts to increase efficiency by one percentage point only pay off if the additional capital cost requirement is below 76 €/kW at investment costs of 1800 €/kW. The higher the investment costs, the lower this hurdle becomes: at 2000 €/kW, the hurdle drops to 66 €/kW. Therefore, R&D should only deploy a mechanism to improve the efficiency if the additional capital investment is below this threshold.

In summary, we can conclude that investment costs are the main factor influencing power plant economics. This is mainly due to two reasons. First, there is a far lower portion of variable costs in overall generation costs in CCS plants, making efficiency less relevant. Second, the greater uncertainty and therefore wider range of expectations for investment costs between 1450 and 2950 €/kW naturally cause a greater impact than efficiency, whose expectations range between 37% and 44%. The relevance of these two factors is further analyzed in the section that follows.

## 4. Relevance of commercial coal-fired CCS plant economics for expected market size

### *4.1. Approach*

As a next step, we analyze how European-wide market penetration of CCS coal power plants varies, given certain investment costs and efficiencies. This provides a view as to what extent these uncertainties drive the potential CCS market size. We initially define a Base Case (section 4.2) using the average economics outlined in Table 1b for a CCS hard-coal plant that can endogenously be built within our simulation model. In a next step, we run sensitivities on investment costs (section 4.3) and efficiencies (section 4.4), leaving all other parameters as in the Base Case, in order to understand the impact of these factors. In section 4.5, we test for $CO_2$ price robustness by varying the $CO_2$ price development of the Base Case, and re-run the sensitivities on investment costs and efficiencies.

To analyze market deployment of CCS, we use HECTOR, a model that simulates the European electricity market bottom-up and that is based on hourly matching of variable-cost based supply bids from power plants with national electricity demand until 2040[5]. The model

[5] For details, see LOHWASSER and MADLENER (2009).

simulates the energy markets of 19 European countries[6] individually and for every hour, considering the national plant portfolios, wind patterns, electrical energy demand patterns, and import/export transmission capacities to other countries. Each power plant, aggregated into about 400 groups with similar technical and economic characteristics, individually bids its full or partial capacity at a bid price based on its variable and opportunity costs to its local energy market (e.g. EEX) that matches demand and supply. Only for renewables does the model use (primarily) historic production patterns for dispatch and policy targets for the development of installed capacity. The model further incorporates opportunistic behavior of power plant operators through a mechanism that increases bid prices when the expected regional reserve margins become low. This approach is able to closely approximate historic wholesale electricity prices, simulating an average price across Europe's main regions[7] between 2006 and 2008 of 54.5 €/MWh compared to 54.8 €/MWh in reality. Further details of the HECTOR model, its modules, data sources, and comparisons with historic values are provided in LOHWASSER and MADLENER (2009).

The high resolution of hourly simulation until 2040 provides endogenously determined variable cost-based market prices and utilization as a consequence of a plant's position in the constantly updated merit order curve. High utilization again causes more full-load hours and therefore greater distribution of fixed costs, lowering the COE and increasing profitability – the driver of investments. This is because the HECTOR model endogenously decides on capacity investments based on the expected NPV of power plant investments, considering all expected future revenues (based on utilization as a result of its own variable cost-based bids) as well as costs (both variable and fixed)[8]. The approach therefore explicitly considers the feedback loop between efficiency and capacity utilization, unlike most publications cited in section 1 or the analysis in section 3 that also used a COE based on full costs, but with static utilization.

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[6] EU-15 excluding Luxembourg and Ireland and including Norway, Switzerland, Czechia, Hungary, Poland and the Slovak Republic, grouped into 14 regions.

[7] Germany (EEX), Italy (IPEX), France (PowerNext), Spain (OMEL) and Scandinavia (NordPool).

[8] For non-nuclear fossil fuel plants, namely hard coal, lignite, natural gas (combined cycle and open cycle) and oil-fired plants. Capacity investments for renewables and nuclear are not built endogenously but through external input, as they are primarily driven by EU policy targets (renewables) or political decisions (nuclear) and to a lesser extent by economic profitability.

*4.2. Base Case*

For our Base Case, we use the same assumptions as in section 2, but have to impose several additional assumptions for the future development of fuel prices, $CO_2$ costs, electrical energy demand levels, and renewables production. For this, we utilize an integrated outlook on the energy and transport sector, published by the EU Commission's DG-TREN (2008)[9], that incorporates the EU's current 20% renewables and 20% $CO_2$ emission reduction targets (EU COMMISSION, 2008). For fuel prices, DG-TREN expects rather flat coal prices at 10-11 €/boe[10] and increasing natural gas prices, starting at 33 €/boe in 2010 and increasing to 38 €/boe in 2030. Oil prices follow the same trend as gas prices. $CO_2$ allowance prices start at 20 €/t in 2010, increase to 43 €/t in 2020, and reach 49 €/t in 2030. All prices are inflation-adjusted to 2005. For electricity demand growth, DG-TREN expects on average 1.2% for the EU countries modeled between 2010 and 2030. To limit complexity within the scenarios, we only analyze CCS for hard coal plants, as they are the largest user of this technology, and therefore do not include CCS for lignite, biomass, or natural gas plants. The CCS hard coal power plant is available after 2020 and has the average economics reported in Table 1b, i.e. investment costs of 1864 €/kW and a 40.4% efficiency. Together with the currently existing national power plant portfolios, net transmission capacities (NTCs), and electricity demand patterns of the European countries included in the model, we simulate the Base Case.

In Figure 2, we see the aggregated capacity development across all 19 European countries simulated as a result of the HECTOR model run. Starting right after the commercial availability in 2020, the share of CCS hard coal plants continuously increases and reaches 143 GW or 14.6% of generation capacity by 2025. The strong presence of CCS undermines the focus on GHG mitigation as a consequence of the EU's 20% reduction target and the corresponding results of DG-TREN (2008), especially $CO_2$ prices, which are favorable for CCS. The strong presence is also in line with expectations from the IEA's World Energy Outlook 2008 450 ppm scenario, that predicts 363 GW of CCS capacity worldwide by 2030, mainly in OECD countries (IEA, 2008).

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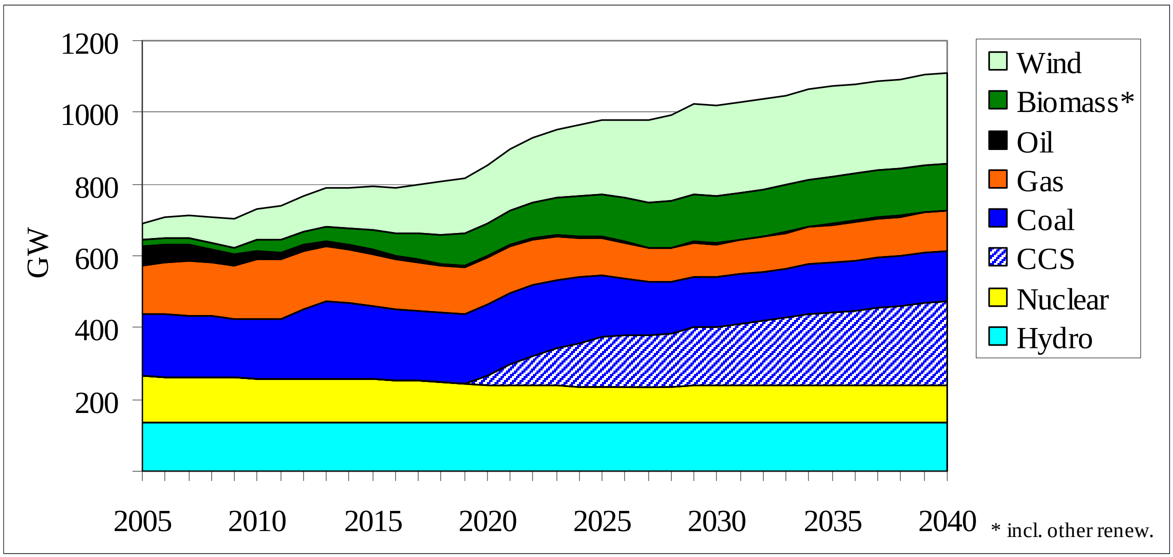
[9] Scenario IV from DG-TREN (2008).

[10] boe = Barrels of Oil Equivalent is the approximate amount of energy released by burning a barrel of crude oil. (1 boe = 6.12 GJ).

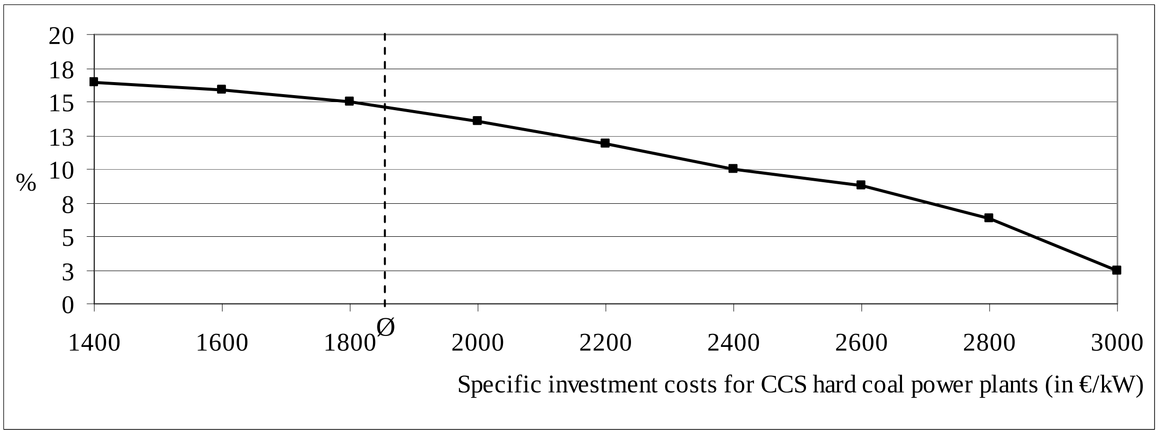
**Figure 2: Installed total generation capacity development across all model regions, Base Case**




## *4.3. Sensitivity to changes in investment costs*

Figure 3 depicts the outcome of a partial factor variation of investment costs, showing the ratio of CCS hard coal capacity in overall European power generation capacity in the year 2025. Every point thereby represents an individual, new simulation run with altered investment costs for CCS hard-coal power plant capacity, and all other input parameters held constant. The range for the sensitivity is derived from the values reported in Table 1b (rounded to hundreds of Euros).

**Figure 3: Share of European CCS capacity in 2025 (in %) as a function of specific investment costs**



We see that the overall success of the technology (in terms of market share) largely depends on the unit investment costs. The upper end of investment costs, at 3000 € per kW of generation capacity, leads to almost no adoption of the new technology. Only 23 GW of new CCS hard coal capacity will be commissioned in this scenario by 2025. In the Base Case, at investment costs of 1864 €/kW, the modeling results foresee 143 GW of capacity in Europe, positioning the technology as a major contributor to electricity generation. The lower end of investment costs, at 1400 €/kW, leads to 164 GW of installed CCS plant capacity. On an aggregated European level, we can therefore conclude that the investment costs will be a key driver for the success of the technology. The difference between the lowest and highest investment cost expectation is 141 GW of capacity. The corresponding European market size for coal-fired CCS power plants ranges between € 69 billion (23 GW at 3000 €/kW) and € 230 billion (164 GW at 1400 €/kW) for the five years after their commercial availability in 2020 – a tremendous potential, but paired with great uncertainty.

This wide range observed for the diffusion of CCS also has a strong implication for anthropogenic $CO_2$ emissions. Before CCS is deployed, we experience a steady decline in $CO_2$ emissions within the energy sector, mainly due to the increased penetration of renewables on account of the EU policy targets. This leads to an overall reduction in Europe's $CO_2$ emissions from the electricity generation sector of 11% by 2020 compared to 2010 (1096 Mt in 2020 vs. 1237 Mt in 2010). If we assume average investment costs of 1864 €/kW, we observe a $CO_2$ emission reduction of 51% by 2025 compared to 2010. This represents a drop of 491 Mt within the first five years after CCS technology has become commercially available (605 Mt in 2025 vs. 1096 in 2020). Compared to the High Inv. case, which hardly deploys CCS at all by 2025, the resulting $CO_2$ abatement is also minimal: Total emissions across all modeled countries are, at 1112 Mt in 2025, merely 10% below 2010 standards. Therefore, CCS investment costs and the resulting impact on deployment play a major role in GHG abatement. This also means that if the high investment costs of 3000 €/kW materialize, the other industry sectors – transportation, industry, etc. – will have to reduce their emissions by an additional 507 Mt $CO_2$ by 2025 in order to compensate for CCS and to achieve the levels of the Base Case, a value that would endanger overall reduction targets on the European level. The development of $CO_2$ emissions in the electricity generation sector in dependence of investment costs is depicted in the appendix in Figure A1.

The CCS capacity development on the European level is an aggregation of the EU's heterogeneous countries and their individual production portfolios and demand shapes. Table 4 shows the generation mix for the model's individual countries for three scenarios by 2025: The low investment cost scenario ('Low Inv.') with 1400 €/kW, representing the lower end of the observations in Table 1b, the Base Case with 1864 €/kW, representing the average investment costs, and the high investment cost scenario ('High Inv.') with 3000 €/kW, representing the upper end of investment cost expectations. For comparison purposes, Table A2 in the appendix summarizes the current capacities as of 2009. In the Base Case, the Netherlands, with a CCS capacity share of 19% by 2025, exhibit the highest share in Europe, followed by the combined Germany, Austria, and Switzerland ('D-A-CH') region, Greece and the UK with 14-16%. Belgium, Czechia, Poland, Slovakia, and Hungary each realize 10-13%. France, despite its nuclear-intensive portfolio, still constructs 7% of CCS capacity, mainly due to increased electricity demand of about 2% p.a. after 2020, which is not addressed through additional nuclear power plants[11]. Finally, Spain and Portugal hardly utilize the CCS technology, achieving only 4%, mainly due to the large new renewable power generation capacities expected post-2020. Denmark, Finland, Norway, and Sweden do not deploy the technology at all in the Base Case, which remains unchanged in the Low Inv. scenario. This strong deployment changes significantly when the investment costs are increased to 3000 €/kW in the High Inv. scenario: except for the Netherlands, no country achieves a deployment level beyond 5%.

This variety in CCS adoption on the European level is the result of individual national developments. To analyze and understand these developments, we need to explicitly consider the existing plant portfolio and resulting base/peak load economics on the regional level and over time. For this, we focus on the combined Germany, Austria, and Switzerland region, as it nicely shows most national effects caused by this technology. The region also, in absolute terms, deploys most CCS capacity, currently features all existing generation technologies, including lignite and nuclear, and is large enough so that the construction of a single CCS hard coal plant of 900 MW does not significantly alter the power plant fleet, i.e. the solution is more robust.

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[11] The simulation model only constructs conventional capacity (coal, gas, oil) endogenously. Nuclear capacity development, just like for renewables, is taken as an exogenous input, as we assume political targets rather than economic potential to be the key driver of deployment. If no decommissioning dates are announced for nuclear power plants, we assume reinvestments to extend the lifetime. Further details can be found in LOHWASSER and MADLENER (2009).

**Table 4: Installed total capacity in Europe 2025 (in GW)**

| Country | Low Inv. scenario (1400 €/kW) | | | Base Case (1864 €/kW) | | | High Inv. scenario (3000 €/kW) | | | Scenario-independent | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CCS | Coal* | Gas** | CCS | Coal | Gas | CCS | Coal | Gas | Nuc. | RES*** |
| Belgium | 4 | 5 | 3 | 4 | 5 | 3 | 1 | 6 | 4 | 1 | 8 |
| Czechia | 5 | 7 | 0 | 5 | 7 | 0 | 0 | 8 | 0 | 4 | 7 |
| Denmark | 0 | 3 | 1 | 0 | 3 | 1 | 0 | 3 | 1 | 0 | 7 |
| Finland/Norway/Sweden | 0 | 7 | 9 | 0 | 7 | 9 | 0 | 7 | 9 | 14 | 66 |
| France | 29 | 15 | 3 | 16 | 15 | 3 | 0 | 19 | 4 | 56 | 51 |
| Germany/Austria/Switzerland | 41 | 39 | 9 | 41 | 39 | 9 | 9 | 63 | 16 | 3 | 89 |
| Greece | 5 | 3 | 4 | 5 | 3 | 4 | 1 | 5 | 5 | 0 | 8 |
| Hungary | 2 | 2 | 5 | 2 | 2 | 5 | 0 | 2 | 5 | 2 | 4 |
| Italy | 12 | 11 | 30 | 12 | 11 | 32 | 4 | 16 | 43 | 0 | 41 |
| Netherlands | 9 | 7 | 10 | 9 | 7 | 11 | 4 | 9 | 14 | 0 | 10 |
| Poland | 11 | 19 | 0 | 10 | 19 | 0 | 2 | 23 | 0 | 3 | 24 |
| Slovakia | 2 | 1 | 2 | 2 | 1 | 2 | 0 | 2 | 2 | 2 | 4 |
| Spain/Portugal | 14 | 16 | 7 | 9 | 16 | 11 | 1 | 18 | 15 | 4 | 85 |
| UK | 31 | 35 | 17 | 31 | 36 | 17 | 3 | 42 | 25 | 9 | 57 |

* Coal capacity represents hard coal and lignite capacity not using CCS technology

** Incl. oil-based generation capacity of negligible quantity

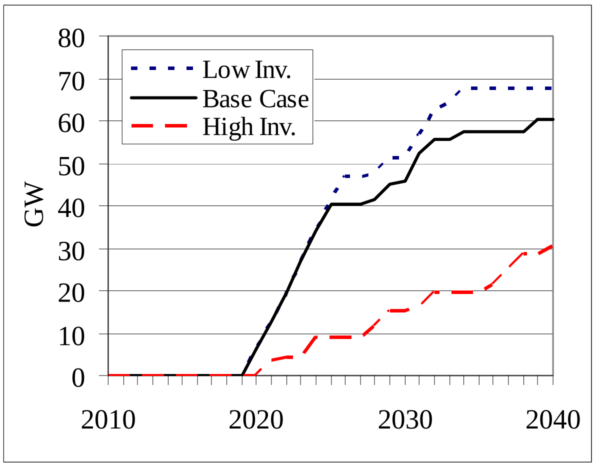
*** Renewable Energy Sources (RES): Wind, Biomass, Hydro, Solar, Geothermal, and other renewables

For this D-A-CH region, we show the development of CCS capacity in Figure 4a, where we observe a large difference between the three scenarios. For the first five years both in the Base Case and Low Inv. scenario, the model builds CCS power plants as fast as it can due to continuously positive NPVs in these years. Only by 2025 (Base Case) or 2026 (Low Inv.), do market prices drop down sufficiently to slow down investments. In the Low Inv. scenario, the model even reaches the $CO_2$ storage limitation by 2034. We see a contrasting picture when looking at the regular, non-CCS hard coal capacity in Figure 4b: Once CCS hard coal is coming online, half of the non-CCS coal capacity is retired, as it is forced out of the market by CCS capacity.

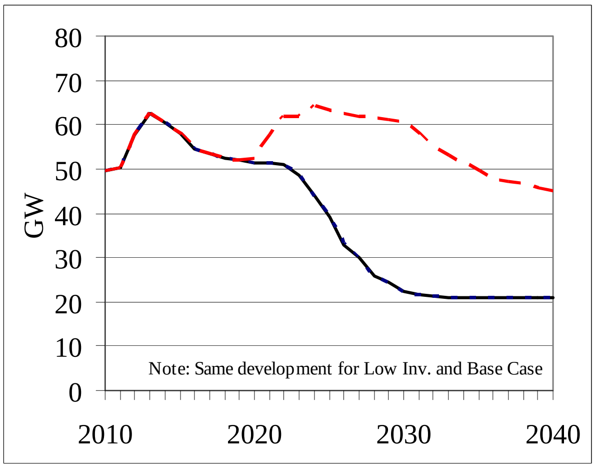
We see from Table 4 that increased CCS hard coal capacity primarily replaces conventional coal rather than natural gas capacity. Specifically, comparing the max investment cost scenario with the Base Case, we see 32 GW of additional CCS capacity forcing 24 GW of old coal power plants but only 7 GW of old natural gas power plants out of the market. Nuclear and renewable plants have lower variable costs than CCS coal plants and their merit-order position therefore remains unchanged. This does not apply to conventional coal and natural gas plants, as the new CCS plants operate at lower variable costs than their non-CCS counterparts, shifting the merit order curve to the right, i.e. causing lower utilization for non-CCS coal and natural gas plants. Coal, however, as a capital-intensive technology with high start-up and shut-down costs, is less able to cope with the lower utilization than natural gas plants, whose costs primarily arise from variable components. This drop in utilization for non-CCS supercritical hard coal plants can be seen in Figure 4d.

**Figure 4: Hard coal plant capacity and utilization in the D-A-CH region, 2010-2040**

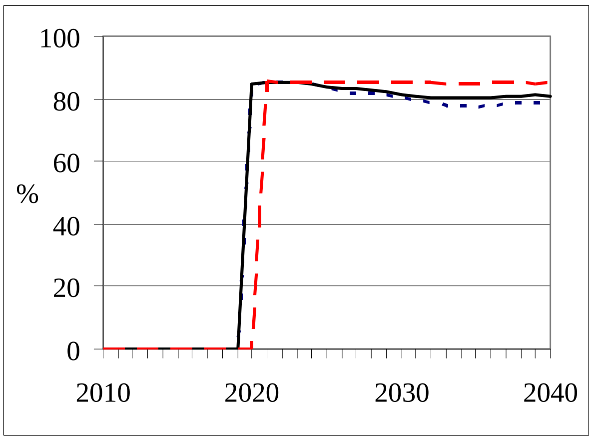
(a): CCS capacity



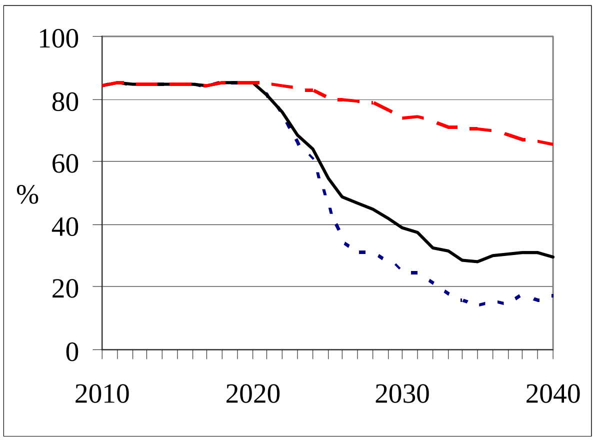

(b): Non-CCS capacity




(c): CCS utilization




(d): Non-CCS utilization (only supercritical plants)

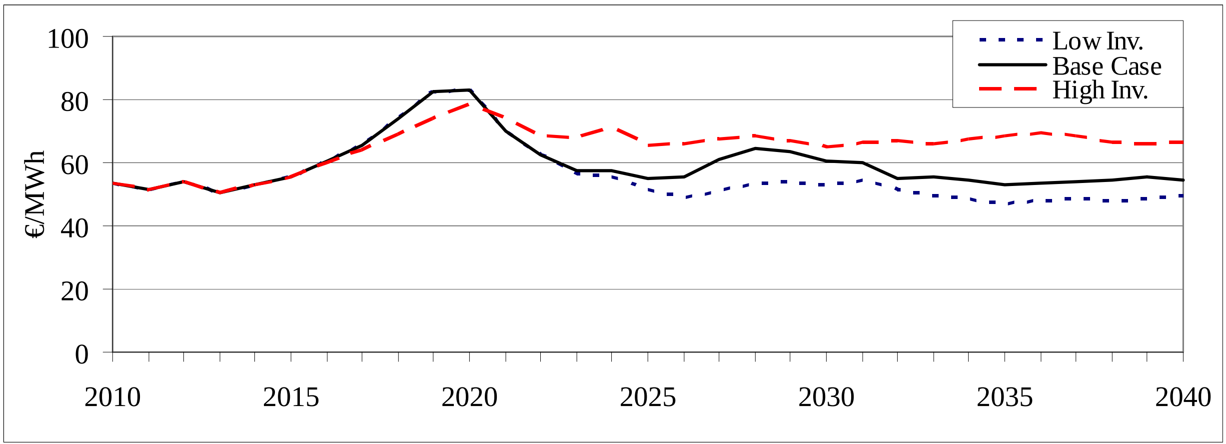



With the strong CCS deployment in the Base Case, the utilization of modern, supercritical coal power plants without CCS decreases from currently above 80% to eventually 30%. While running only 30% of the time, it is almost impossible to recover the fixed costs incurred by such a capital-intensive technology, even with high market prices. CCS technology, on the other hand, has replaced non-CCS coal capacity as base load supplier, and continuously achieves utilization rates in the 80% range (Figure 4c), a value now typical for current coal plants. The rate is higher for the High Inv. scenario, as less CCS capacity exists in the market.

Considering this development, utility companies with large coal generation capacities are practically forced to look into CCS in the low and average investment cost scenarios, as their existing portfolios are endangered most by this new technology. Natural gas-focused utilities, on the other hand, are impacted less.

In terms of electricity price, as depicted in Figure 5, we notice an average base load price of 59.0 €/MWh in the period where CCS is available (2020-2040). Even though this value is lower than the overall COE for coal-fired CCS plants of 65.9 €/MWh reported in section 3, the environment is still profitable for these plants, as the expected fuel costs for hard coal are lower than historical values by 2020[12] and, as a second reason, the plant is not running at full base load, allowing it to shut down in low-priced hours.

**Figure 5: Average annual wholesale electricity price development in the D-A-CH region, 2010-2040**




The availability of CCS and its large deployment in the Base Case leads to a drop of on average 9.2 €/MWh after the technology becomes available in 2020, compared to the limited CCS deployment in the High Inv. scenario. Even before the plants come online in 2020, we

[12] The COE analysis in section 3 was based on the historic average over the years 2005 and 2008, which is 90 US$/t. The expectations of DG-TREN (2008), that serve as an input for our Base Case, however, expect 60 US$/t in 2020, leading to a lower COE for CCS-equipped coal-fired power plants.

notice a difference in electricity prices: This is because investors in the model know about power plants soon after construction begins (a five-year process for a CCS hard coal plant). The large expected investments in CCS post-2020 lower the expected electricity market price and therefore the NPVs of new plants, leading to slightly less capacity and a higher price before 2020 in the Base Case and the Low Inv. scenario compared to the High Inv. scenario.

Once the plants come online in 2020, the low variable costs of CCS plants and therefore the lower bidding price cause a shift of the merit order to the right, making technologies with lower variable costs price setters. With only low CCS market penetration, as in the High Inv. scenario, there is no electricity price dip caused by CCS, and prices reach a fairly high level, driven mainly by high $CO_2$ prices.

### *4.4. Sensitivity to changes in conversion efficiency*

After the sensitivity to investment costs, we now look into scenario runs with a variation of the efficiency of CCS hard coal power plants. The range between 37% and 44% is again taken from the minimum and maximum observations shown in Table 1b, resulting in the high efficiency ('High Eff.') scenario with 44% and low efficiency ('Low Eff.') scenario with 37%.

Unlike the previous investment cost sensitivity results shown in Figure 3, that imply a range of CCS capacity share in Europe between 2.5% and 16.5%, we now only observe a narrow range between 13.2% and 15.4% (Figure 6). This confirms the outcome of the COE analysis reported in section 3, stating that investment costs are an economically more relevant source of uncertainty than efficiency. Yet, the extent of the low impact of this uncertainty is surprising, as it effectively negates the relevance of efficiency improvements for CCS hard coal power plants. This result is also consistent across the 19 European countries considered, as shown in Table 5. On top of the reasons already mentioned in the COE analysis, this is due to merit order curve effects and resulting base/peak load economics in the markets: CCS hard coal capacity takes a position before non-CCS coal and natural gas power plants, but after nuclear and renewables capacity, as depicted in Figure 7. The two horizontal lines in the figure highlight its variable electricity production costs, 26 €/MWh in the Base Case (40% efficiency) and 28 €/MWh in the Low Eff. scenario (37% efficiency). The difference is only 2 €/MWh, which is low compared to the average market price of 55 €/MWh and very unlike investment costs, where the difference in COE between 1864 €/kW (avg.) and 3000 €/kW (max.) is 13 €/MWh. The result is also fairly robust, as there is a large gap to lignite, which is next on the merit order curve with variable costs that are 14 €/MWh higher. As long as the variable costs of electricity generation do not increase beyond this level, CCS plants will benefit from a full base load position and therefore high capacity utilization. In this situation, efficiency would need to drop below 29% to reach the variable costs of lignite, a value that is below today's value of 33% for CCS plants.

**Figure 6: Share of European CCS capacity in 2025 (in %) as a function of conversion efficiency**

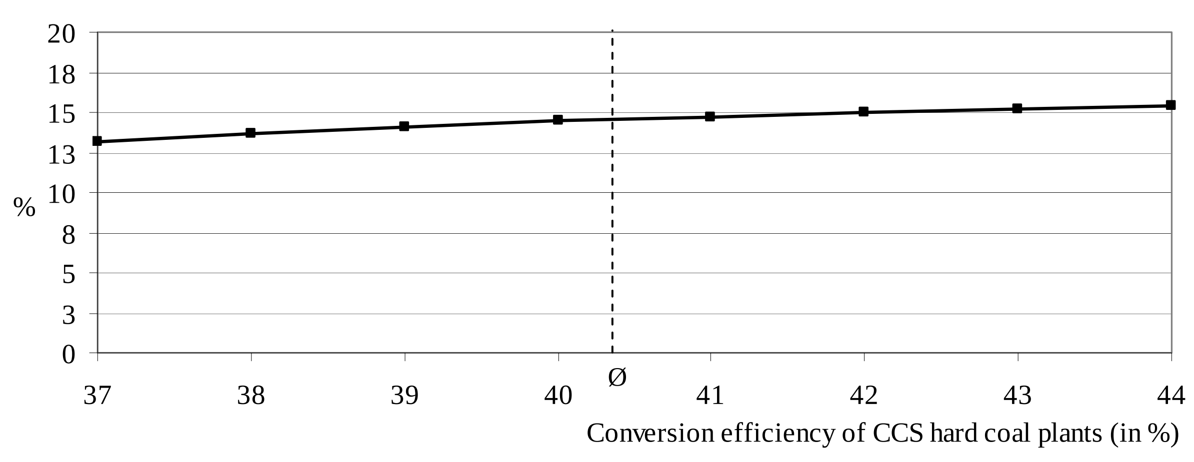



**Table 5: Installed total capacity in Europe 2025 (in GW)**

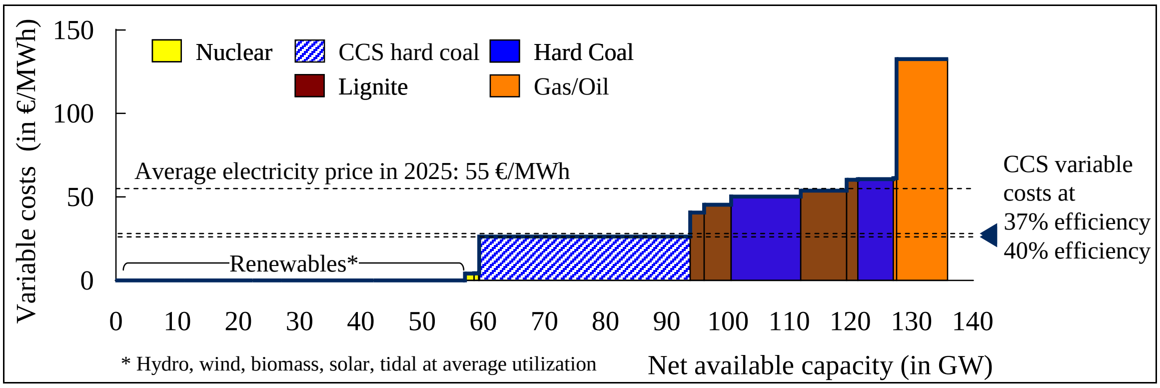
| Country | Low Eff. scenario (37% efficiency) | | | Base Case (40% efficiency) | | | High Eff. scenario (44% efficiency) | | | Scenario-independent | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CCS | Coal* | Gas** | CCS | Coal | Gas | CCS | Coal | Gas | Nuc. | RES*** |
| Belgium | 4 | 5 | 3 | 4 | 5 | 3 | 4 | 5 | 3 | 1 | 8 |
| Czechia | 4 | 7 | 0 | 5 | 7 | 0 | 5 | 7 | 0 | 4 | 7 |
| Denmark | 0 | 3 | 1 | 0 | 3 | 1 | 0 | 3 | 1 | 0 | 7 |
| Finland/Norway/Sweden | 0 | 7 | 9 | 0 | 7 | 9 | 0 | 7 | 9 | 14 | 66 |
| France | 12 | 16 | 4 | 16 | 15 | 3 | 23 | 15 | 3 | 56 | 51 |
| Germany/Austria/Switzerland | 37 | 40 | 9 | 41 | 39 | 9 | 41 | 39 | 9 | 3 | 89 |
| Greece | 5 | 3 | 4 | 5 | 3 | 4 | 5 | 3 | 4 | 0 | 8 |
| Hungary | 1 | 2 | 5 | 2 | 2 | 5 | 2 | 2 | 5 | 2 | 4 |
| Italy | 12 | 12 | 35 | 12 | 11 | 32 | 12 | 11 | 31 | 0 | 41 |
| Netherlands | 9 | 7 | 11 | 9 | 7 | 11 | 9 | 7 | 10 | 0 | 10 |
| Poland | 8 | 19 | 0 | 10 | 19 | 0 | 10 | 19 | 0 | 3 | 24 |
| Slovakia | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 4 |
| Spain/Portugal | 9 | 16 | 11 | 9 | 16 | 11 | 11 | 16 | 9 | 4 | 85 |
| UK | 29 | 37 | 17 | 31 | 36 | 17 | 31 | 36 | 17 | 9 | 57 |

* Coal capacity represents hard coal and lignite capacity not using CCS technology

** Incl. oil-based generation capacity of negligible quantity

*** Renewable Energy Sources (RES): Wind, Biomass, Hydro, Solar, Geothermal, and other renewables

**Figure 7: Merit order curve for the D-A-CH region, Base Case, 2025**




### *4.5. Robustness to $CO_2$ price changes*

As $CO_2$ allowance prices are a key driver for deployment of CCS, we now test the robustness of the results for three additional $CO_2$ price developments between 20 and 50 €/t in 2020, that are outlined in Table 6. With even lower $CO_2$ prices (e.g. 10 €/t), the model predicts no CCS power plants at all, regardless of investment cost and efficiency combinations. For every $CO_2$ price scenario, we conduct the same sensitivity analysis for investment costs as in section 4.3 and for efficiency as in section 4.4, respectively.

**Table 6: Scenario description for $CO_2$ price robustness tests**

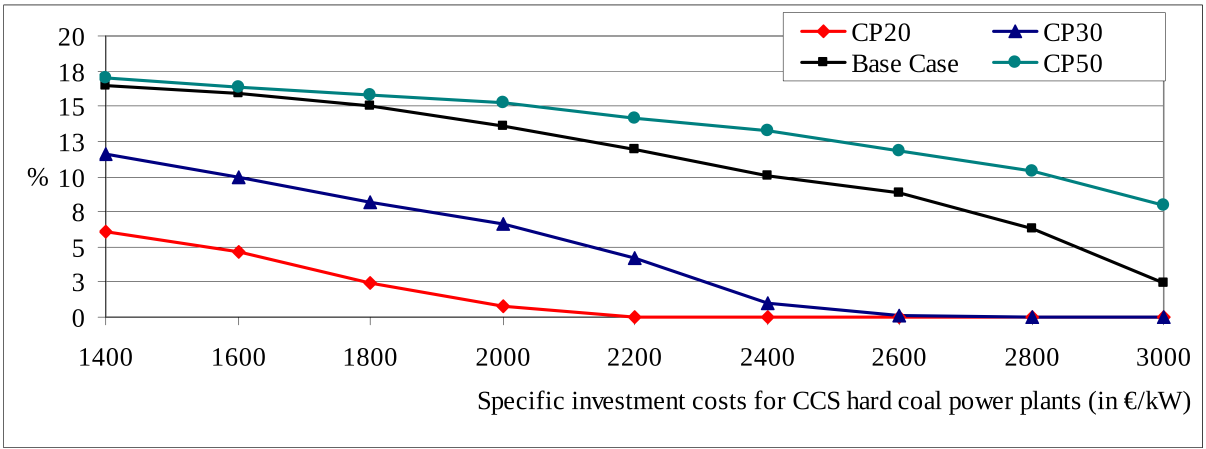
| | | $CO_2$ allowance price in year | | | | |
|---|---|---|---|---|---|---|
| **Scenario name** | **Description** | 2010 | 2015 | **2020** | 2025 | 2030 |
| Base Case | Development as of DG-TREN, 2008 | 20 | 34 | **43** | 46 | 49 |
| CP20 (Carbon Price 20 €/t) | $CO_2$ price of Base Case -23 €/t | 0 | 11 | **20** | 23 | 26 |
| CP30 (Carbon Price 30 €/t) | $CO_2$ price of Base Case -13 €/t | 7 | 21 | **30** | 33 | 36 |
| CP50 (Carbon Price 50 €/t) | $CO_2$ price of Base Case +7 €/t | 27 | 41 | **50** | 53 | 56 |

For the investment cost sensitivity, we see in Figure 8a that if CCS enters the market in the first place, deployment reacts very sensitively to this factor. The relationship between a change in investment costs and the corresponding impact on market deployment is very similar for $CO_2$ prices of 20 and 30 €/t to the Base Case in the area where any CCS is built at all. In this area, starting below 2000 €/kW for the CP20 scenario, we have on average 1.8 percentage points of additional CCS deployment in Europe for every 200 €/kW investment cost reduction. The CP30 scenario starts deployment below 2400 €/t and reaches on average

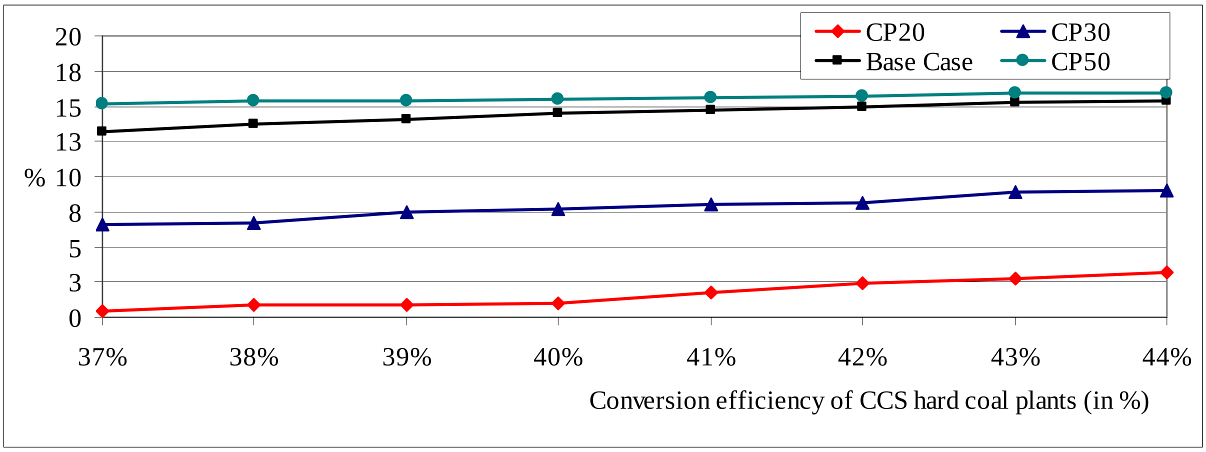
1.9% of additional CCS deployment for every 200 €/kW investment cost, whereas the Base Case has on average 1.8%. For the CP50 scenario, we notice a flatter curve compared to the Base Case, mainly as $CO_2$ storage limitations are reached in some regions, prohibiting further capacity additions. This also leads to on average only 1.1% additional CCS deployment for every 200 €/kW investment cost reduction.

Comparing this to the sensitivity towards efficiency shown in Figure 8b, we again see that the conclusions previously drawn are relatively robust towards changes in $CO_2$ prices. The CP20 scenario has on average 0.39 percentage points additional deployment for every percentage point efficiency increase, the CP30 scenario 0.35 percentage points. In comparison, the Base Case reacts slightly less sensitively with 0.32 percentage points additional deployment for every percentage point efficiency increase. Noticeable is that even though the absolute impact of efficiency variation remains relatively similar for the lower $CO_2$ price scenarios, the relative impact increases, as the overall level of CCS deployment is significantly lower for these scenarios. In the CP20 scenario, it leads to hardly any deployment (0.5%) at 37% efficiency or to at least some deployment (3.2%) if 44% efficiency is assumed. Compared to investment costs, this still is a low impact (0.0% deployment at >2200 €/kW vs. 6.1% deployment at 1400 €/kW).

**Figure 8: Share of European CCS capacity in 2025 for different $CO_2$ price scenarios (in %)**
(a) As a function of specific investment costs



(b) As a function of conversion efficiency

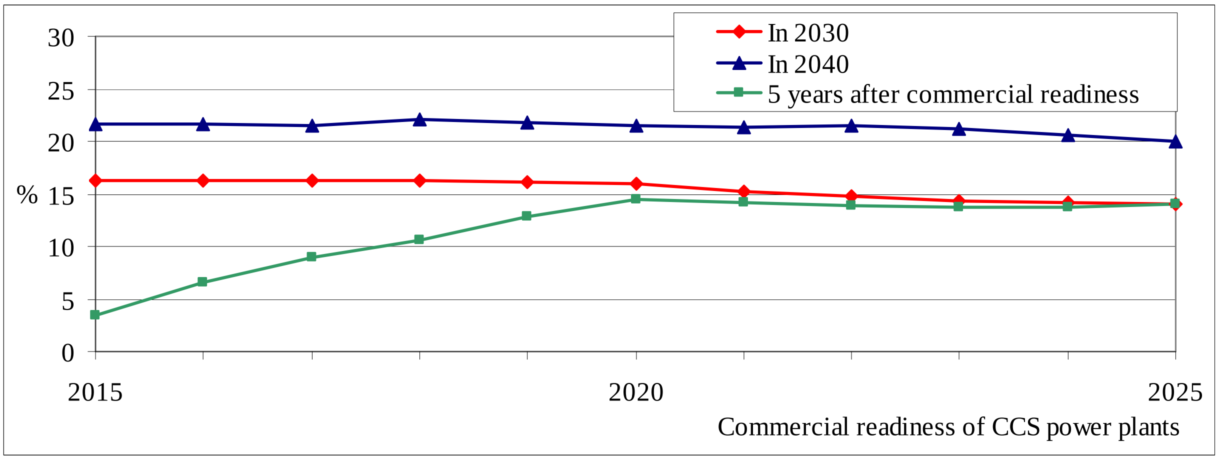



*4.6. Sensitivity towards commercial readiness*

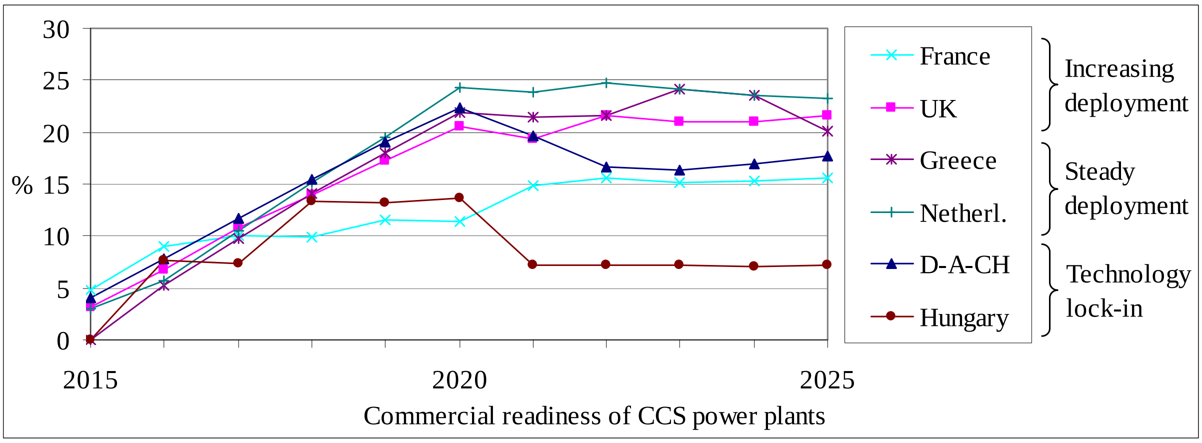
A prerequisite for the previous analysis is technological availability at large scale. However, as research for CCS capture technology is still at an early stage, it is difficult to estimate when the technology will be ready for commercial use. Whereas the literature review outlined in Table 1b highlights the year 2020 as the most likely date for commercial readiness, there remains a significant amount of uncertainty. Yet, availability by 2020 is vital from a climate change point of view, as even a ten-year delay would be economically serious (HASZELDINE, 2009 and MCKINSEY, 2009). A delay can also lead to "lock-in effects" of inferior environmental technologies (UNRUH, 2000, 2002). Specifically, these are coal- and gas-fired power plants without CCS, constructed to satisfy demand, as CCS technology is unavailable. The long lifetime of this new capacity and the saturated market overly lower the attractiveness of CCS beyond the pure delay of deployment. The lock-in effect is further detailed, e.g. in CARRILLO-HERMOSILLA (2005).

To analyze the impact on market diffusion in case of a postponed/delayed commercial availability of CCS power plants beyond the previously assumed year 2020, we conduct a five year sensitivity. We additionally simulate a hypothetical early commercial readiness to identify potential lock-in effects that might already be in effect with a deployment starting 2020, leading to a sensitivity range spanning over the years 2015 to 2025. All other parameters, including the economics of CCS power plants, are identical to the Base Case outlined in section 4.2. The overall results on the European level are outlined in Figure 9a, the development for selected European countries in Figure 9b.

**Figure 9: Share of CCS in total generation capacity as a function of commercial availability (in %)**
(a) On a European level, for selected points in time




(b) For selected individual countries, CCS capacity share five years after commercial readiness




On a European level, we see that overall CCS diffusion in the years 2030 and 2040 is relatively stable and unaffected by the year of commercial readiness. The difference in deployment between a commercial availability in 2020 compared to 2025 is only 2.0 percentage points by 2030 and 1.4 percentage points by 2040. Therefore, we can conclude that there is no substantial lock-in effect observed on a European level. However, while a late availability does not lead to a noticeably smaller CCS capacity by 2030, it is problematical from a climate point of view, as $CO_2$ abatement also starts at a later point in time, which lowers the cumulative effect.

Comparing the CCS deployment not at a certain date but dynamically within five years after commercial availability (lowest line in Figure 9a), we see a continuous increase of deployment for a commercial readiness between 2015 and 2020, followed by a relatively constant development for a readiness between 2020 and 2025. This is mainly due to the $CO_2$ price development, a key driver for economic attractiveness of CCS plants. Between 2015 and 2020, the $CO_2$ price increases in the Base Case by 9 €/t, from 34 €/t to 43 €/t. During the next five years, it is only 3 €/t, from 43 €/t to 46 €/t.

When considering the CCS deployment for the individual European countries, we see a relatively heterogeneous picture. Figure 9b shows the deployment five years after the initial availability of commercial CCS power plants for selected countries. National developments can be loosely grouped along three main themes of development listed below. For the countries Denmark, Finland, Sweden, and Norway, no CCS capacity is constructed in the model regardless of the simulated scenario, due to insufficient economic attractiveness; these countries are therefore not categorized.

- *Increasing deployment:* The rate of deployment for CCS power plants continuously increases with the delay in commercial readiness. This is effectively the opposite effect of a technological lock-in and can be observed for France and, to a lesser extent, also the UK, Spain, and Portugal.

- *Steady deployment:* Between CCS availability years 2015 and 2020, the deployment rate increases along with the $CO_2$ price development, but stagnates for a deployment beyond 2020. This is the same result as previously described for the aggregated European level, and can be observed for the countries Netherlands, Greece, Italy, Belgium, and Poland.

- *Technological lock-in:* After reaching a deployment rate high around 2020, the rate drops, due to other, non-CCS capacity coming online to satisfy the demand that CCS was unable to address. This technology lock-in effect can be observed for the countries of the combined D-A-CH region, Hungary, Czechia, and Slovakia.

Aggregating all European countries, we see that there is no technology lock-in effect observed on a European level, but rather a fairly steady development for a deployment after 2020. This is due to the heterogeneous structure of European generation portfolios, that evens out any technology lock-in effect of individual countries. Therefore, in terms of CCS deployment by 2030 and 2040, we can conclude that the impact on European market diffusion caused by a delay in commercial readiness of CCS is not significant. Instead, other factors, such as investment costs, are more relevant, as outlined in the previous sections.

## 5. Conclusions

In this article, we have shown expectations for economics of commercial-grade CCS coal-fired power plants, and how their uncertainty may impact market deployment. The range of expectations published in a literature review lies between 1400-3000 €/kW for investment costs, 37-44% for efficiency, and 30-74 €/kW/year for fixed costs. The uncertainties around plant lifetime, $CO_2$ capture ratio, and variable O&M costs are, on the other hand, rather low.

When converting these ranges into total costs of electricity generation, the uncertainty regarding investment costs bears the largest economic impact, with a difference between the maximum to minimum investment costs causing a range of 18 €/MWh in electricity generation costs (COE) compared to only 6 €/MWh for efficiency.

To investigate the findings of the highly simplified but very transparent approach of a pure cost of electricity (COE) analysis, we applied the sophisticated HECTOR electricity market model, that simulates power plants hourly in 19 European countries individually and bottom-up. The results in 2025 confirm the previous results and show that the average investment costs of 1864 €/kW lead to results with 143 GW CCS hard coal capacity or 14.6% of European installed total generation capacity. The high end of investment cost observations, at 3000 €/kW, is enough to virtually preclude CCS from the market with 2.5% CCS in European power generation capacity. The lower end, 1400 €/kW leads to 16.5%.

This is very different for efficiency, where the observed range of 37% to 44% leads to market diffusion between 129 and 152 GW of CCS hard coal capacity or 13.2%-15.4% of Europe's capacity. The hypothesis of the COE-based analysis is thereby confirmed, but to a far greater extent.

We find that this is due to two main effects:

1. CCS lowers the share of variable costs in overall generation costs from 77% to 55% for hard coal plants, thereby reducing the cost addressable through efficiency. Therefore, improving efficiency has relatively lower impact on overall generation costs. This is due to $CO_2$ allowance costs as a key component of variable costs for non-CCS plants, which are of far lower relevance for CCS plants. The difference between the average efficiency of 40% and the minimum observation of 37% increases the variable costs from 26 to 28 €/MWh in 2025, insignificant considering the average market price of 55 €/MWh in that year (Base Case).

2. Merit order curve dynamics place CCS hard coal plants with their very low variable costs well ahead of traditional coal- and natural gas-based technology in the supply curve. It is therefore established as a base load technology with high utilization. The gap to the next technology is very wide, with about 50% of their own variable costs in the Base Case, so CCS hard coal plants are not prone to run mid merit and are only displaced by renewables and nuclear plants. This is a shift from the dynamics of current coal and natural gas plants, that are all comparably close in terms of variable costs and therefore dispatch order, a reason why efficiency is the focus of non-CCS plants (ECOFYS, 2008).

These conclusions on the relevance of investment costs over efficiency also hold true at $CO_2$ price levels above and below the 43 €/t in 2020 assumed in the Base Case – provided that CCS enters the market at all in the first place. In the low $CO_2$ price scenarios (CP20, CP30) we only see limited CCS diffusion, so even the small changes caused by efficiency changes lead to, relatively speaking, a large impact on CCS deployment. However, the impact of investment cost on European deployment of CCS in the CP20 scenario is still twice as large as the efficiency sensitivity, with both sensitivities covering the min/max values derived from the literature review. Also a sensitivity analysis for the date of commercial availability of CCS produced robust results, with no technological lock-in effects observed on a European level.

In summary, we conclude that the impact of CCS on the economics of coal-fired power plants imposes a shift of priorities from the currently prevailing focus on efficiency towards investment costs. We therefore believe that current CCS R&D efforts should explicitly consider this for trade-off decisions, maximizing the gains that can be reaped from improving both investment costs and efficiency.

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## Appendix

**Figure A1: $CO_2$ emissions from the electricity generation sector in all model regions, 2010-2040**

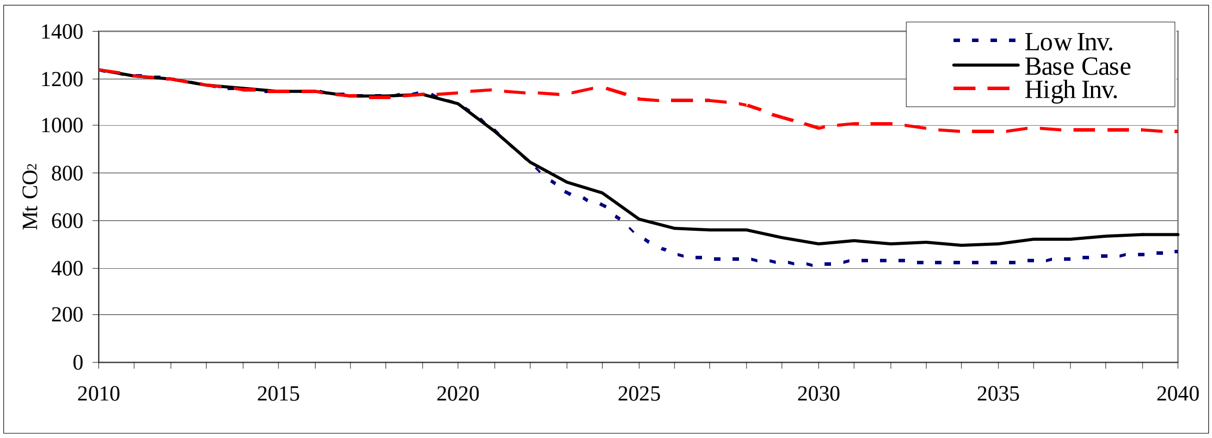


**Table A2: Installed total capacity in Europe 2009 (in GW)**

| Country | Low Inv. scenario (1400 €/kW) | | | Base Case (1864 €/kW) | | | High Inv. scenario (3000 €/kW) | | | Scenario-independent | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CCS | Coal* | Gas** | CCS | Coal | Gas | CCS | Coal | Gas | Nuc. | RES*** |
| Belgium | 0 | 4 | 6 | 0 | 4 | 6 | 0 | 4 | 6 | 6 | 3 |
| Czechia | 0 | 9 | 1 | 0 | 9 | 1 | 0 | 9 | 1 | 3 | 3 |
| Denmark | 0 | 5 | 4 | 0 | 5 | 4 | 0 | 5 | 4 | 0 | 4 |
| Finland/Norway/Sweden | 0 | 5 | 11 | 0 | 5 | 11 | 0 | 5 | 11 | 10 | 49 |
| France | 0 | 11 | 9 | 0 | 11 | 9 | 0 | 11 | 9 | 63 | 26 |
| Germany/Austria/Switzerland | 0 | 49 | 25 | 0 | 49 | 25 | 0 | 49 | 25 | 21 | 57 |
| Greece | 0 | 6 | 4 | 0 | 6 | 4 | 0 | 6 | 4 | 0 | 4 |
| Hungary | 0 | 2 | 5 | 0 | 2 | 5 | 0 | 2 | 5 | 2 | 0 |
| Italy | 0 | 6 | 45 | 0 | 6 | 45 | 0 | 6 | 45 | 0 | 21 |
| Netherlands | 0 | 4 | 13 | 0 | 4 | 13 | 0 | 4 | 13 | 0 | 4 |
| Poland | 0 | 23 | 1 | 0 | 23 | 1 | 0 | 23 | 1 | 0 | 5 |
| Slovakia | 0 | 1 | 2 | 0 | 1 | 2 | 0 | 1 | 2 | 2 | 1 |
| Spain/Portugal | 0 | 13 | 25 | 0 | 13 | 25 | 0 | 13 | 25 | 8 | 40 |
| UK | 0 | 28 | 27 | 0 | 28 | 27 | 0 | 28 | 27 | 11 | 16 |

* Coal capacity represents hard coal and lignite capacity not using CCS technology
** Incl. oil-based generation capacity of low quantity
*** Renewable Energy Sources (RES): Wind, Biomass, Hydro, Solar, Geothermal, and other renewables

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