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Tackling long-term climate change together: the case of flexible CCS and fluctuating renewable energy

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Abstract

The present study aims at shedding light into the interaction of fluctuating renewables and the operational flexibility of post-combustion capture plants in the framework of a long-term model. We developed a model of the electricity sector taking into account both long-term investment time scales to represent plant fleet development under economic and climate constraints as well as short time scales to consider fluctuations of demand and renewable energy sources. The LIMES model allows us to determine the respective roles of renewables and CCS in climate change mitigation efforts within the electricity sector. Furthermore, we assess the influence of natural gas prices on fuel choice and investigate the shares of competing CCS approaches in the technology mix. We find that the optimal technology mix includes large shares of renewables and simultaneously different competing CCS technologies, depending on emission constraints and fuel prices.

Keywords: Climate Change Mitigation; Variability; Renewables; flexible operation; CO_2 capture

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1. Introduction

Assessments of long-term, global mitigation technology strategies[1] highlight the important role of carbon capture and sequestration (CCS) and renewable energy technologies (RET) for the decarbonization of the electricity sector. The Integrated Assessment Models (IAMs) used in such studies consider long time frames to determine optimal investment streams in different low carbon technologies while short term variability of renewable energy sources and demand are represented only on a very simplified level (e.g., see [12]). Consequently, the need to balance variability is not fully represented in the model structure and, thus, the optimal investment choices are subject to critique. The model assumptions may generally overestimate the potential to decarbonize the electricity sector, because balancing of fluctuations might require - at least to some extent - the use of fossil fuels. Hence, the role of RETs may be smaller than suggested by IAMs , especially if stringent emission targets are to be met.

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[1] The model intercomparison projects presented in [5] and [13] give an example of such assessments.

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Several technology options are available to enable integration of RETs into the electricity system: backup provided by conventional power plants, storage technologies, long-distance electricity transmission and demand side management. Flexible natural gas powered turbines are often considered one of the main options for balancing of fluctuations of renewable energy electricity generation. However, another option might be available: several studies show that coal power stations with post-combustion capture are sufficiently flexible to balance short-run fluctuations ([2, 3, 4, 16]). Steam that is used in the carbon capture unit can be quickly re-allocated to power a turbine while venting the CO_2 in the flue gas. Thus, electricity output as well as CO_2 emissions are temporarily increased to fulfill requirements set by the power system. This operational flexibility of the post-combustion concept is not represented in standard energy system models and consequently not appreciated in the optimal solution of technology choice. An assessment of competing CCS approaches such as oxyfuel and post-combustion technologies is thus necessary to determine their respective roles in carbon-free electricity generation. Additionally, the availability of both flexibly operated CCS coal power plants and natural gas powered turbines for fluctuation balancing raises the question of the influence of fuel prices on the chosen technology mix.

The present study analyses the interaction of fluctuating renewables and the operational flexibility of post-combustion capture plants in the framework of a long-term model. We developed LIMES (Long-term Investment Model for the Electricity Sector), a model of the electricity sector[2] taking into account both long-term investment time scales to investigate plant fleet development under economic and climate constraints as well as short time scales to represent fluctuations of demand and renewable energy sources. The model presented in this paper allows us to answer the following questions: How large are the respective roles of RETs and CCS in the climate change mitigation efforts within the electricity sector? Are competing CCS approaches part of the technology mix simultaneously? Finally, how do natural gas prices affect technology choices?

The remainder of this article is structured as follows: Section 2 highlights important features of the extended LIMES model, Section 3 presents results of the analysis and Section 4 concludes.

2. The extended LIMES model

For the purpose of this investigation, a single-region model of the electricity sector is implemented and calibrated to data[3] of the area of Germany that is covered by the transmission system operator 50Hz Transmission GmbH (formerly Vattenfall Europe Transmission, covering mainly East Germany and Hamburg). A complete model description can be found in [9], this section will illustrate the most important model features as well as extensions made for this study. The model is developed as an intertemporal optimization with the possibility to set emission constraints It takes a social planner perspective with perfect foresight. Fluctuations that arise due to varying demand and fluctuating output of wind energy and solar PV capacities are represented by dividing a year into various characteristic periods ('time slices'). The time slices differentiate variations between seasons, days of the week and phases of the day. From the original data, mean electricity demand is determined for each time slice as well as capacity factors for wind and solar energy. To illustrate the concept of time slices, Figure 1 shows demand for 16 time slices of the year 2007. Neighboring bars represent 6h intervals for the spring, summer, autumn, and winter season. The model allows for usage of different temporal resolutions i.e. different number of time slices. [9] investigates the influence of the chosen temporal resolution on model results. For the analysis in this paper we choose 48 time slices, representing one characteristic day for each season, each of these days subdivided into 2h steps. Along with mean output from wind within each time slice, we consider variations happening on shorter time-scales by analyzing the change of wind electricity generation between different time intervals. From the analysis of these variations, we derive requirements for backup capacities needed within the system and supplementary electricity generation for system balancing.

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[2] The model version presented in this paper consists of a one region setup calibrated to data for the area of East Germany and Hamburg.

[3] We use time series for 2007 with a 15 minute resolution for electricity demand and wind and solar power feed-in which are publicly available on http://www.50hertz-transmission.net/

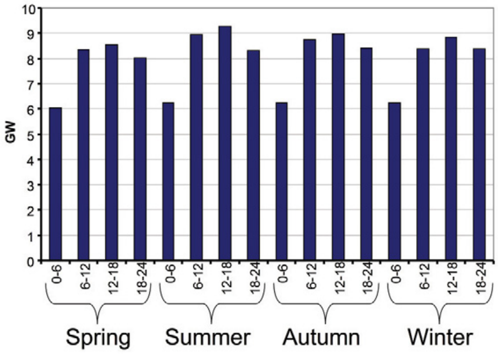

Figure 1: Mean demand in time slices

The model includes 15 different technologies for producing electricity and one storage technology. This choice is based on the technologies currently installed in the region considered and additional options such as different carbon capture and sequestration technologies. As an addition to the standard model version, we include the possibility to turn off post-combustion capture for lignite power plants. The implementation considers a fleet of capture-equipped power plants and allows for the model to choose the share of facilities using capture within each time slice. When capture is turned off, the energy yield is increased but specific emissions increase. As the model uses a budget for emissions allowed over the time-frame considered, emissions will have to be saved elsewhere.

There are several reasons for limiting the flexibility option to post-combustion capture for lignite plants: First, hard coal only plays a minor role in electricity generation in the region considered in this model. Second, while according to [3], turning off CO_2 capture in oxyfuel equipped plants might be technically feasible, the higher complexity of the process does not allow for an easy bypass of the capture-induced energy penalty. Coal power stations with carbon capture following the pre-combustion concept are not considered to exhibit this flexibility.

East Germany is assumed to act as a price taker for several fossil fuel types. Prices for internationally traded hard coal, oil and natural gas are derived from [11] for the period of 2005 to 2050, and a constant increase of 2% over 5 years is assumed for the second half of the century. For the price of domestic lignite, we assume a growth rate of 5% p.a. starting from the numbers given in [6]. Furthermore, to represent the lignite open cast mine situation in the region, we restrict available resources to mines already approved (2.5 GtC). In line with [14] a total potential of 6.34 GtC for carbon sequestration is presumed for Germany. We assume that one third of this potential (2.11 GtC) is available for the region considered in our model. Power plants equipped with Post-Combustion CCS (PC+CCS, Lignite+CCS, NGCC+CCS) display a capture rate of 90% while Oxyfuel plants are assumed to capture 95% of emissions. Electricity demand in LIMES is given exogenously. We start from numbers for the year 2007 obtained from the internet database of 50Hertz Transmission GmbH[4]. An increase of 0.2% per 5 years is assumed as this region is expected to experience a moderate development of energy demand. We use an interest rate of 5% p.a. in the model.

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[4] http://www.50hertz-transmission.net/cps/rde/xchg/trm_de/hs.xsl/149.htm

Table 1: Techno-economic parameters (Based on [1, 10, 8])

Technology[5]	Investment costs[6]	Fixed O&M costs	Variable O&M costs	Thermal efficiency	Initial capacity
	\$/kW	% Inv. Cost	\$/GJ	%	GW
PC	1740	3	1.07	44	0.5
PC + CCS[7]	3000	3	2.67	36	-
PC + Oxy	2680	3	2.14	37	-
Lignite	1875	3	1.07	43	9.3
Lignite + CCS	3000	3	2.67(CCS on) /1.35 (CCS off)	34 (CCS on)/ 43 (CCS off)	-
Lignite + Oxy	2680	3	2.14	35	-
DOT	500	3	0.79	30	-
NGT	440	3	1.59	32	1
NGCC	810	2	0.53	56	-
NGCC + CCS	1370	2	0.94	48	-
Wind (onshore)	1500	3	0	-	9.5
PV	6100	1.5	0	-	0.3
Hydro	3740	2	0	-	0.009
TNR	-[8]	3	1.21	33	2.1
PHS	1250	0.38	0.94	85	2.9

3. Results

To assess the influence of capture flexibility and the respective roles of CCS technologies and RETs, we perform a series of model experiments using different setups concerning fuel prices and technology availability. The scenarios are analyzed regarding the deployment of RET and CCS plants as well as other technologies that address balancing requirements. In particular, we look at the technology choice of alternative CCS plants. Furthermore, we assess the costs of emission mitigation and how they are affected by the availability of flexible CCS technologies.

3.1. Reference Cases

The first reference (REF_{off}) case for this analysis consists of a policy experiment with a cumulative budget for emissions over the model time-span. We adapted the emission budget proposed by [15] for Germany by using a target of 0.9 GtC until 2150 for the region examined here.[9] The REF_{off} case has all technologies available except for storage but does not allow for flexible switching of carbon capture. The electricity mix, which can be seen in Figure 2, displays large shares of lignite technologies and wind energy. Natural gas technologies play a role, mainly for balancing purposes, and lignite plants with oxyfuel capture enter the mix starting in 2050 to allow reaching the climate protection target.

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[5] Abbreviations: PC - Pulverized Coal Power Plant (Hard Coal), CCS - Carbon Capture and Sequestration (Post-Combustion), Oxy - Oxyfuel Capture, Lignite - Lignite Power Plant, DOT - Diesel Oil Turbine, NGT - Open Cycle Gas Turbine, NGCC - Natural Gas Combined Cycle, Wind - Wind Turbine, PV - Solar Photovoltaics, Hydro - Hydroelectric Power Plant, TNR - Thermonuclear Reactor, PHS - Pumped Storage

[6] All US\$ Values refer to 2005 values.

[7] CCS denotes post-combustion capture in this model setting.

[8] Electricity generation from nuclear power plants is phased out until 2030 and no investments into new nuclear capacities are possible for the model to represent current German policy on nuclear energy.

[9] [15] propose a cap of 3GtC for all energy production in Germany, which we reduced to 0.9 GtC, since we only consider one part of Germany and only electricity generation.

When allowing for flexible operation of post-combustion lignite power plants ($\mathrm{REF_{on}}$ case, see Figure 3), the picture changes: the amount of natural gas is reduced from 3.8% to 2.3% of cumulated electricity generation and lignite CCS plants enter the electricity mix. These capacities partly replace the older, inflexible lignite plants, which leads to their early introduction in about 2025. While used solely without capture until 2055, post-combustion plants start operating with flexible usage of capture in 2060. After 2075, the technology is almost exclusively used with capture turned on to allow for complying with the imposed emission budget. Figure 4 shows time slices for the year 2065 as an example for the usage of flexible capture within the model. Capture is switched off during the days, when electricity demand is high, while nighttime production is performed with carbon capture.

Lignite oxyfuel plants, being the slightly less expensive option, are the preferred lignite based technologies while aiming for climate protection targets. However, due to the flexibility exhibited by its post-combustion counterpart, both alternatives are deployed concurrently[10]. The emission budget used in this setup plays an important role in the choice of technologies for electricity generation: A sensitivity analysis concerning the chosen emission budget revealed that for cumulative caps below 0.8 GtC, flexible post-combustion power plants are no longer used and oxyfuel capture is the technology of choice. The higher capture rate of oxyfuel facilities is an important asset which outweighs the increased balancing abilities and additional energy output from flexibly operated post-combustion CCS plants.

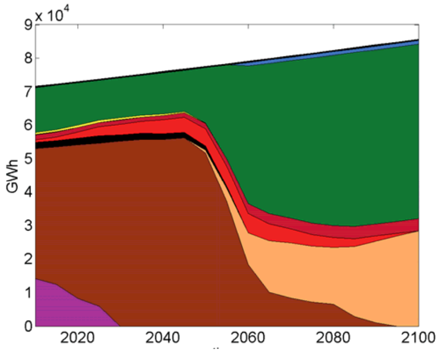

Figure 2: Cumulative yearly electricity production without capture flexibility (REFoff case)

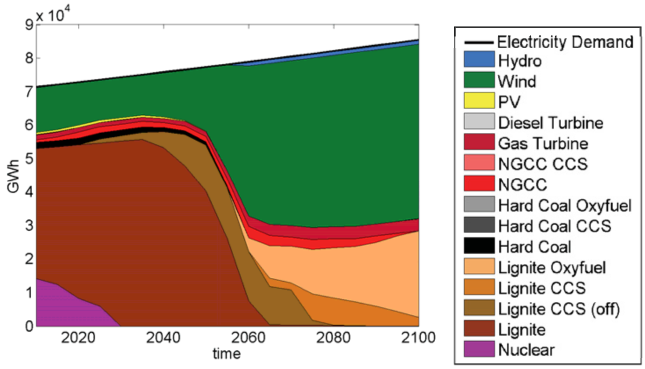

Figure 3: Cumulative yearly electricity production with capture flexibility (REFon case)

3.2. Cost Assessment

An assessment of total discounted energy system costs for the $\mathrm{REF_{off}}$ and $\mathrm{REF_{on}}$ cases shows that the availability of flexible capture leads to an (albeit small) reduction of costs from 54.57 billion US$ to 54.41 billion US$. The reduction is mostly due to the reduced amount of natural gas that is used in the $\mathrm{REF_{on}}$ scenario. Lower energy system costs also induce a reduction of climate change mitigation costs[11] from 1.8% to 1.5% of energy system costs. There are two effects that cause mitigation costs to be relatively low: the emission budget is relatively weak and high wind shares are already present in the case without any climate policy. Since the installed capacities for wind energy in East Germany are already at about 9GW (in 2007), the emissions in the no policy case mostly originate from burning large amounts of lignite. While wind energy and lignite power plants with CCS constitute the least

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[10] Due to uncertainty concerning the effective difference in investment costs for post-combustion and oxyfuel technologies, we performed experiments with varying ratios for investment costs. Higher costs for oxyfuel lead to less usage of the latter and more post-combustion plants while the range of years where these are operated with flexible switching of capture remains unchanged.

[11] Mitigation costs are calculated by comparing costs from the policy runs to a business-as-usual (BAU) case without any climate policy measures and no forced extension of renewable energy technologies.

expensive mitigation options and thus take up large shares of the electricity mix, natural gas capacities deployed for balancing strongly influence energy system costs. Flexibly operated post-combustion CCS reduces this role, but its impact is relatively small. To assess the interaction of natural gas capacities and post-combustion CCS under different scenarios, we perform a sensitivity analysis on natural gas prices in Section 3.3.

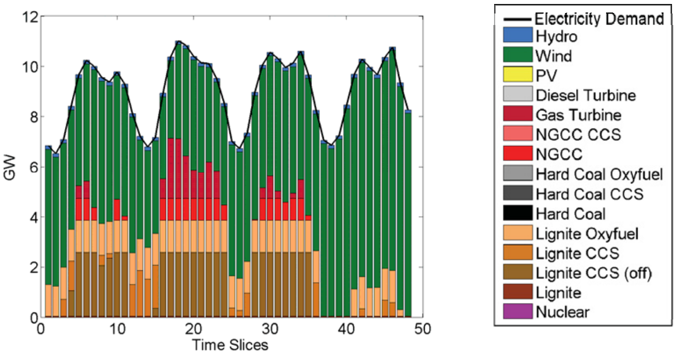

Figure 4: Electricity generation in the year 2065 for the REF$_{on}$ case

3.3. Sensitivity to natural gas prices

As mentioned in Section 3.1, introduction of flexible lignite post-combustion displaces electricity generation from gas combined cycle plants and reduces the overall share of natural gas in the energy mix. The reference case REF$_{on}$ uses a gas price starting at 6\$/GJ in 2005, increasing to about 20\$/GJ in 2100. To assess the influence of the gas price on technology choice, we conduct a sensitivity analysis using different price paths for natural gas by adding a constant markup of -3\$/GJ to +2\$/GJ to the initial curve. Figure 5 displays the cumulative electricity generations for the time period of 2005 to 2100 that result from this variation. While balancing constraints require a certain amount of electricity generation from gas turbines, the amount of natural gas used in combined cycle plants decreases for model runs with higher gas prices. For an initial gas price below 4.5\$/GJ, natural gas is preferred over lignite with oxyfuel capture. The additional emission from natural gas (which are half those of lignite without capture) are offset partly by reductions after 2100, partly by a reduced usage of lignite. While flexible usage of post-combustion lignite plays a role in all scenarios, its relative share rises for initial prices between 3.5 and 6\$/GJ and remains more or less constant beyond 6.5\$/GJ. This points to a threshold for this technology, where additional flexible output increase is offset by the lower costs and lower emissions of oxyfuel capture facilities.

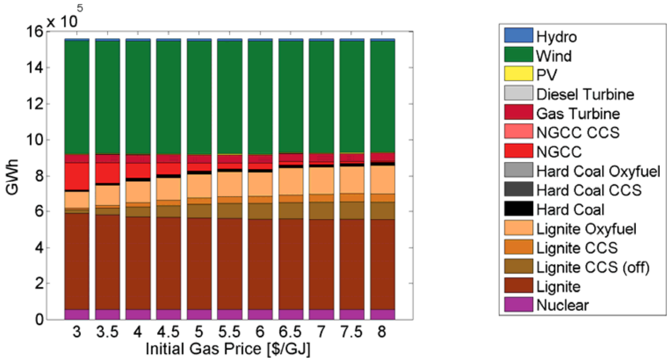

Figure 5: Cumulated electricity generation for 2005-2100 for different gas price scenarios

3.4. Technology availability and constraints

In addition to the analyses presented above, we conduct two technological assessments: We examine the influence of storage availability on model results and introduced a must-run constraint on wind power plants to represent current policies on renewable power feed-in.

The availability of pumped hydro storage introduces an additional technology to balance variations in electricity demand and renewables availability over the different time slices. While energy losses from storage require additional electricity generation, the latter is mostly produced from wind, thus reducing curtailments and saving fuel costs and emissions. These advantages lead to a clear preference for storage as flexibility option over post-combustion lignite and also partly over natural gas. Lignite CCS is still used but oxyfuel equipped facilities are preferred. Figure 6 presents the resulting cumulated electricity generation, which includes large shares of wind and lignite, some natural gas and lignite oxyfuel. Storage usage reduces energy system costs by 9.8% (compared to the REF_{on} scenario), mostly through natural gas cost savings and by limiting investments to one CCS technology.

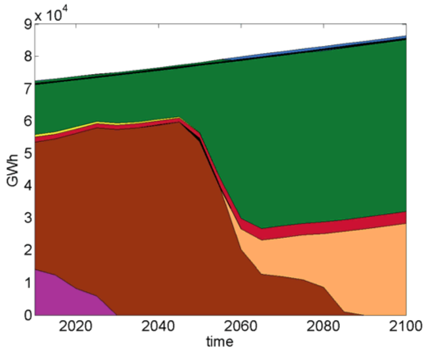

Figure 6: Cumulated electricity generation with storage

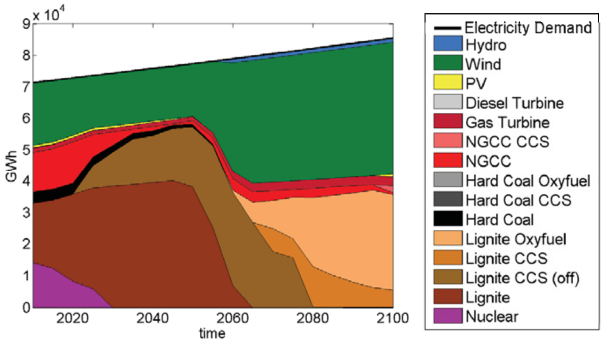

Figure 7: Cumulated electricity generation with must-run constraint for wind

To represent feed-in priority policies for renewables, which exist in several countries, e.g. Germany, we introduced a must-run constraint for wind energy. In contrast to the reference cases, curtailments of wind energy are not possible in this case. Figure 7 displays electricity generation for this scenario. A comparison with Figure 3 shows increased shares in natural gas combined cycle and lignite CCS electricity generation. These flexible technologies allow for balancing of the wind variations throughout the year, contrary to the more inflexible older lignite plants or oxyfuel plants. A large increase of new lignite capacities after 2020 can be attributed to the increased need for flexible operation, as it is assumed that older lignite plants are unable to fulfill balancing requirements. The reduced share of wind energy together with more natural gas and new lignite capacities leads to 13.1% higher energy system costs than in the REF_{on} scenario. Despite its higher costs, the importance of flexible post-combustion for balancing purposes is strongly increased in this scenario.

4. Conclusion and outlook

We present the LIMES model to evaluate the importance of flexible operation of post-combustion CCS plants and to gain insight on optimal technology scenarios for climate change mitigation. Results show a mix of technologies: large amounts of wind energy balanced by natural gas, flexible post-combustion lignite plants or storage technologies. Furthermore, oxyfuel capture plays an important role in base-load electricity generation with low emissions. Introducing flexible capture switching for post-combustion as an additional balancing option leads to a reduction of the natural gas share in the power mix and thus to a reduction of overall costs. The significance of this option is strongly sensitive to the imposed emission budget and prices for natural gas as well as the availability of other technologies. Constraints on curtailments for wind energy lead to additional balancing necessities and increase the share of natural gas and post-combustion power plants. Flexible operation of post-combustion capture for power plants should thus be considered as a technological option in the context of climate change mitigation. However, availability of oxyfuel capture, renewable energy technologies and storage reduces the need for post-combustion CCS and it remains debatable whether the role of this technology will be sufficiently large to justify investments into research and development for both this technology and oxyfuel capture.

The current model setup consists of a single region which is treated as being autarkic. While interconnections to the rest of Germany from this region are limited, this restriction neglects balancing of variability through long-distance electricity transmission. A future model version will include more regions interconnected by power lines, as described in [7]. Despite additional constraints to account for wind power variability, the present model setup does not capture all aspects of temporal fluctuations. Improved time slice setups will address this problem in the future.

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