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Bio-IGCC with CCS as a long-term mitigation option in a coupled energy-system and land-use model

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Abstract

This study analyses the impact of techno-economic performance of the BIGCC process and the effect of different biomass feedstocks on the technology's long term deployment in climate change mitigation scenarios. As the BIGCC technology demands high amounts of biomass raw material it also affects the land-use sector and is dependent on conditions and constraints on the land-use side. To represent the interaction of biomass demand and supply side the global energy-economy-climate model ReMIND is linked to the global land-use model MAgPIE. The link integrates biomass demand and price as well as emission prices and land-use emissions. Results indicate that BIGCC with CCS could serve as an important mitigation option and that it could even be the main bioenergy conversion technology sharing 33% of overall mitigation in 2100. The contribution of BIGCC technology to long-term climate change mitigation is much higher if grass is used as fuel instead of wood, provided that the grass-based process is highly efficient. The capture rate has to significantly exceed 60 % otherwise the technology is not applied. The overall primary energy consumption of biomass reacts much more sensitive to price changes of the biomass than to techno-economic performance of the BIGCC process. As biomass is mainly used with CCS technologies high amounts of carbon are captured ranging from 130 GtC to 240 GtC (cumulated from 2005-2100) in different scenarios.

Keywords: Biomass, IGCC, Carbon Capture and Sequestration, Land use, Soft link

1. Introduction

Negative CO_2 emission technologies can play an important role on the way towards a low emissions energy system if they are available at reasonable costs [5]. One way of achieving negative emissions is applying CCS on biomass conversion processes. One promising biomass-to-electricity conversion technology suitable for CCS with a high capture rate is the integrated biomass gasification combined cycle (BIGCC), which is expected to be highly efficient and economically feasible as it is technically similar to the efficient coal IGCC process and can profit from the experiences made with those plants [19]. Moreover, there are several other biomass CCS technologies but with less favorable techno-economic performance. However, only few non-commercial BIGCC demonstration plants

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without CCS have been realized [4, 6]. Thus economic BIGCC studies analyzing different plant configurations are hypothetical. This results in high uncertainty about techno-economic performance of potential BIGCC plants.

Additional uncertainty occurs concerning different biomass raw materials feeding the plant. There are two main types of cellulosic short rotation energy crops: wood (poplar, willow, eucalyptus, pine) and grass (primarily miscanthus). Most techno-economic BIGCC studies assume wood as biomass fuel because it is easier to gasify. But grass is also considered to be a high energetic easy-to-grow short rotation crop. As grass contains more ash, which complicates the gasification and gas cleaning process, it is expected to lower the performance. There is scarce information about the effects of these different biomass fuels on the performance of the overall BIGCC process.

To assess the impact of techno-economic performance of the BIGCC process and the effect of different biomass feedstocks on the technology's long term application in climate change mitigation scenarios we use the global energy-economy-climate model ReMIND [1]. As the BIGCC technology demands high amounts of biomass raw material it also affects the land-use sector and is dependent on conditions and constraints on the land-use side. The production of bioenergy crops causes greenhouse gas (GHG) emissions in the agricultural sector due to fertilisation of dedicated bioenergy crops and land-use change such as deforestation. The rising demand for food and bioenergy production leads to enhanced competition for limited crop land and subsequently to rising prices of biomass, food and water. To represent the dynamic interactions of the energy sector demanding and the agricultural sector supplying biomass for energy production ReMIND is linked to the global land-use model MAgPIE [15]. The link integrates biomass demand and price as well as emission prices and land-use emissions.

Using this integrated modeling framework our study analyses how the BIGCC technology contributes to long term climate change mitigation by answering the following questions:

1. What are the main factors that decide about the application of the BIGCC technology?
2. What is the mitigation potential of the technology?
3. Which biomass-technologies compete with BIGCC in the energy system?

To answer the listed research questions the following scenarios were performed:

- Varying the techno-economic performance: investment costs, electrical efficiency and capture rate,
- choosing different biomass raw materials for the process: grass or wood,
- comparing emissions of a business as usual scenario and a climate policy scenario,

The remainder of this paper is structured as follows: Section 2 first introduces both the energy-economy-climate model ReMIND and the land-use model MAgPIE separately and then explains the model coupling. Moreover it presents the results of a broad literature review concerning the techno-economic characteristics of the BIGCC process. Section 3 gives a detailed description of the scenarios and presents the results. The last section closes with a discussion and outlook on future work.

2. Modeling energy-system and land-use interactions

2.1. The global energy system model ReMIND

The BIGCC technology is integrated into the global energy-economy-climate model ReMIND (Refined model of Investments and Technological Development) that hard-links a macroeconomic growth model with a bottom-up energy system model and a simplified climate module [1]. The macroeconomic growth model of the Ramsey-type solves a general equilibrium problem by maximizing inter-temporal social welfare with perfect foresight subject to constraints of the macroeconomic, the energy and the climate system. This results in optimal distribution of investments among energy conversion technologies in the energy system and in the case of a climate target constraint like it is considered in this study it leads to minimized mitigation costs.

The bottom-up energy system module represents the energy sector on a detailed level of various conversion technologies along the path from primary to final energy production and estimates resulting CO_2 emissions. Technologies are characterized by a set of techno-economic parameters such as specific investment costs, conversion efficiency, operation and maintenance costs or technical life-time. Non-energy GHG emissions (CO_2,

CH_4 and N_2O) from land-use, land-use change and other sources are estimated by marginal abatement cost curves (MAC) [16]. The climate system model calculates the global mean temperature from the accumulation of CO_2 and other GHG [23].

There are multiple bioenergy conversion technologies available in the model: Transportation fuels can be obtained either from Fischer-Tropsch processes (once through or with producer gas recycling) with and without CCS or from a biomass-to-ethanol technology without CCS. Besides the BIGCC plant electricity can be produced by a combined heat and power biomass plant without CCS. A simple biomass heating plant without CCS is also available. Moreover hydrogen can be supplied by gasification of biomass with and without CCS.

As lignocellulosic bioenergy crops are expected to cause much less GHG emissions and less competition with food production in the land-use sector than 1st generation energy crops, the bioenergy technologies considered in this study focus on 2nd generation purpose-grown bioenergy conversion routes. The biomass supply side is represented by the global land-use model MAgPIE. It computes the corresponding biomass price and resulting land-use emissions for a given biomass demand.

2.2. The global land-use model MAgPIE

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global land use allocation model [14, 17, 18]. It takes regional economic conditions as well as spatially explicit data on potential crop yields, land and water constraints into account and derives specific land-use patterns, crop yields, emissions and total costs of agricultural production for each grid cell. Spatially explicit data is provided to MAgPIE on a regular geographic grid, with a resolution of 0.5 by 0.5 degrees. The objective function of the land-use model is to minimize total cost of production for a given amount of agricultural and biomass demand in a recursive dynamic mode. To fulfill the given demands the model can endogenously decide to acquire yield-increasing technological change at additional costs or to convert land from the non-agricultural area into cropland at additional costs.

Regional food demand is defined for an exogenously given population and income growth based on regional diets [7]. Food and feed energy for ten demand categories can be produced by 20 cropping activities and three livestock activities. Biomass demand is also given exogenously and can be satisfied by the production of two cellulose-based bioenergy crops: a grassy (herbaceous) one like Miscanthus and a woody one (ligneous) like Poplar [2]. Residues from forestry and agriculture are not integated. Cropland, pasture land and irrigation water are fixed inputs in limited supply in each grid cell. Variable inputs of production are labour, chemicals, and other capital, which are assumed to be in unlimited supply to the agricultural sector at a given price.

MAgPIE incorporates a representation of the dominant greenhouse gas emissions from land use change and different agricultural activities. CO_2 emissions are caused by land use change and occur if the carbon content of the previous land use activity exceeds the carbon content of the new land use activity. Emissions from agricultural activities focus on N_2O-emissions from the soil and manure storage as well as CH_4-emissions from rice cultivation, enteric fermentation and manure storage that add up to 87 % of total agricultural (land use) emissions in the year 2000 [26]. As agricultural emissions arise from multiple causes, they depend on the type of agricultural activity. Their extent is heavily influenced by crop or animal type, fertilizer input, climate, soil quality or farm management.

2.3. Coupling ReMIND and MAgPIE

To represent the interaction of biomass demand and supply side ReMIND is coupled to MAgPIE via a soft-link meaning that both models stay separated and are solved sequentially in an iteration loop. The link consists of exchanging time paths of certain variables in which the output of one model serves as input for the other model. The link integrates biomass demand and price as well as emissions prices and land-use emissions for CO_2 and N_2O: ReMIND estimates the demand of lignocellulosic biomass and GHG emissions prices for CO_2 and N_2O. Based on this exogenous input, MAgPIE computes corresponding biomass prices and resulting GHG emissions for the given demand. Using this updated information of biomass supply ReMIND is solved again. This is repeated until the exchanged time paths do not show changes from one iteration to the next.

The overall agricultural N_2O emissions estimated by the land-use model are taken as baselines of marginal abatement cost curves within ReMIND from which further abatement is possible. Concerning CO_2 only the additional land-use change emissions due to biomass production are considered. Other land use, land-use change and forestry (LULUCF) CO_2 emissions are covered endogenously by a MAC in ReMIND [8]. Methane is not included into the liking as there is only little direct or indirect effect on CH4 emissions caused by biomass production. Global methane emissions are also estimated endogenously in ReMIND from a MAC.

2.4. Techno-economic characteristic of the BIGCC process

Several suggestions for possible BIGCC process configurations exist. The most important characteristics are the type of biomass raw material input and the design of gasifier, gas cleaning unit and carbon capture process. All plant configurations depicted here use fluidized bed gasifiers as they are appropriate for medium to large-scale application and can cope with varying quality of input material while reducing ash-related problems [29, 28]. The gasifier can be blown with air, steam or oxygen and can be operated at atmospheric or elevated pressure (15-30 bar). Hot gas cleaning is favorable for pressurized gasification whereas for atmospheric gasification cold gas cleaning is preferable. Only few studies consider carbon capture for BIGCC power plants [11, 21, 25]. The CO_2 separation is realized by pre-combustion capture with physical absorption after a water-shift reaction. The gas turbine has to be prepared for low calorific gases like those produced from biomass gasification [22]. However, as there are no commercially running plants, none of these configurations could give proof of being superior in terms of economic feasibility and technological reliability.

From a literature review we obtain techno-economic data of BIGCC-C processes shown in Figure 1 [3, 4, 10, 12, 11, 20, 21, 25, 9]. Both specific investment costs and electrical efficiency show economies of scale. Adding carbon capture to the process increases investment costs and decreases efficiency. For our calculations we use the values displayed in Table 1. As a compromise between large-scale plants which profit from economies of scale and on the other hand costs for transportation of biomass we choose a plant size of 100 MWe [27, 13], which is also in range of the size assumed by several studies (see Figure 1).

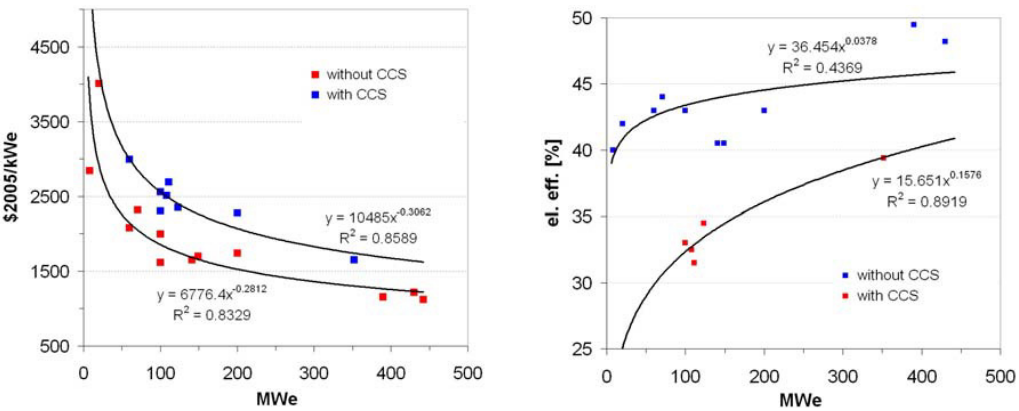

Figure 1: Techno-economic data of BIGCC processes with and without CCS obtained from the literature. Left: Specific investment costs ($2005/kWe) vs. installed capacity (MWe). Right: Electrical efficiency vs. installed capacity (MWe).

		BIGCC	BIGCC+CCS default	BIGCC+CCS 10%	BIGCC+CCS 20%
Plant size	[MWe]	100	100		
Specific investment costs	[$2005/kWe]	1860	2560	2816	3072
Electrical efficiency	[%]	42	31	28	25
Operating capacity factor	[%]	80	80		
O&M costs	[$2005/GJ]	3.95	5.66		
Capture rate	[%]	0	90		

Table 1: Techno-economic parameterization of BIGCC process with and without CCS used in the energy system model.

3. Results

3.1. Mitigation potential

Figure 2 compares emissions of the business as usual scenario (upper black line) which does not impose any restrictions on the energy system emissions to a policy scenario with a limit of a global mean temperature rise of 2°C above pre-industrial level (lower black line). The colored areas in between display the contributions of different mitigation options to the overall emission reductions. Biomass production is limited to grass only. Starting at the middle of the century the BIGCC+CCS technology reaches a share of 33% in 2100 on the overall mitigation. The heavy use of biomass with CCS even facilitates slightly negative total energy system emissions at the end of the century which in turn allows for rising emissions at the beginning of the century.

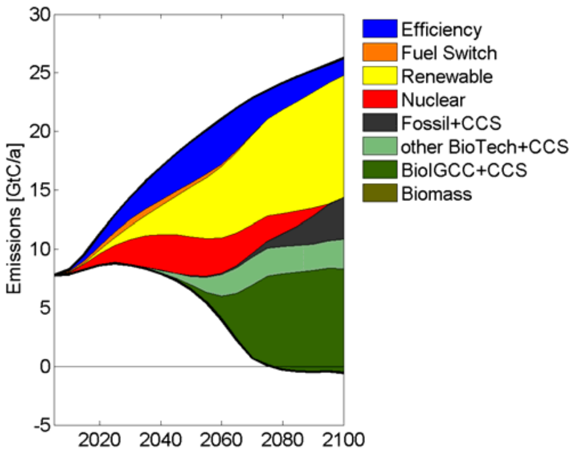

Figure 2: Comparing emissions of business as usual and policy scenario emissions: mitigation shares of technologies, fuel switch and efficiency gains (biomass type: grass).

3.2. Techno-economic performance and biomass type

We perform a sensitivity analysis by varying the techno-economic parameters of the BIGCC+CCS process obtained form the literature. Three cases are considered, as shown in Table 1: (i) default, (ii) electrical efficiency 10% lower and specific investment costs 10% higher than in default case (eff10), (iii) electrical efficiency 20% lower and specific investment costs 20% higher than in default case (eff20). Each case was combined with two different lignocellulosic bioenergy feedstocks, wood (wo) and grass (gr), delivered by the land-use model. For all cases a climate change mitigation target of 2°C is applied.

Figure 3 shows the carbon captured by the BIGCC+CCS process with different techno-economic performances cumulated from 2005-2100. Even in the most pessimistic case of a grass-fed process (gr-eff20) almost the same amount of carbon is captured as in the most optimistic wood-fired scenario (wo). The reason is the lower price for grass, starting at 4 $US/GJ in 2005 and rising to 10 $US/GJ in 2100 compared to wood ranging from 7 $US/GJ to 25 $US/GJ in the same period. However, the grass-fed process is much more sensitive to the degradation of techno-economic performance than the wood fired processes. The results show that the contribution of BIGCC-C technology to long-term climate change mitigation could be much higher if grass is used as fuel instead of wood, provided that the grass process is highly efficient. Even though BIGCC without CCS provides electricity with low carbon emissions it is hardly applied by the model. As can be seen on the right in Figure 3 the most important parameter, which decides about the application of the technology, is the capture rate. It has to significantly exceed 60 % otherwise the technology is not applied.

Almost all biomass is used with CCS technologies resulting in high amounts of captured carbon from 2005-2100. In the case of grass raw material the cumulated captured carbon for all cases of efficiencies and capture rates exceeds 170 GtC and reaches 240 GtC for the most efficient grass-case. In all wood-based scenarios the cumulated amount is lower and accounts for about 130 GtC.

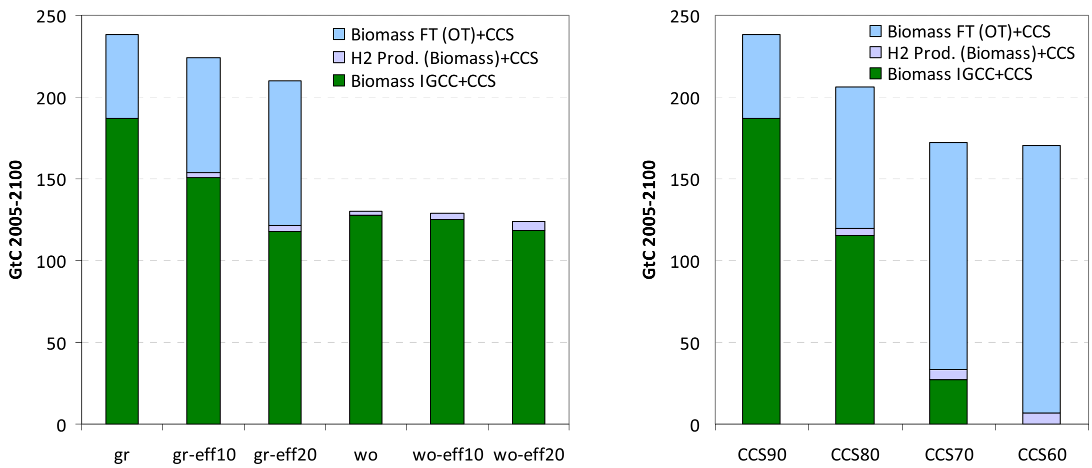

Figure 3: Carbon captured from Bio-CCS technologies cumulated form 2005-2100 in GtC. Left: Variation of techno-economic performance (see Table 1) and biomass fuel. Right: Variation of capture rate: 90%, 80%, 70%, 60% (fuel: grass)

3.3. Competing Biomass Technologies

Figure 3 (right) already points out that a decreasing capture rate leads to less deployment of the BIGCC+CCS technology. As there is no change on the land-use side, the same amount of biomass is still available at same prices. In Figure 4 (right) the share of primary energy consumption of different bioenergy technologies is depicted. It shows the competing technologies which step in when the BIGCC+CCS technology becomes unattractive due to low capture rates. It is the Biomass-to-liquids Fischer-Tropsch technology which takes over and also provides negative emissions as the CCS type of this technology is used. Its capture rate of 48% is lower than in all depicted cases of BIGCC+CCS, but in contrast to BIGCC (that produces electricity) it produces Diesel for the transportation sector and thus helps substituting fossil oil. An opposing trend can be observed if parameters on the energy system side stay constant but biomass prices rise (represented here by a fuel switch from grass to wood). As Figure 4 (left) shows, the BIGCC+CCS technology displaces the Fischer-Tropsch technology as it can provide more negative emissions from the more expensive biomass. The cumulated amount of biomass used from 2005-2100 in all efficiency cases of the more expensive raw material wood is about 5500 EJ, which is less than half of the amount used in all efficiency cases with grass (about 12500 EJ). This shows that if biomass is scarce it is predominantly used by the BioIGCC+CCS technology to produce as much negative emissions as possible. Moreover the overall primary energy consumption of biomass reacts much less sensitive to techno-economic performance of the BIGCC (efficiency and capture rate) process than to price changes of the biomass (grass and wood).

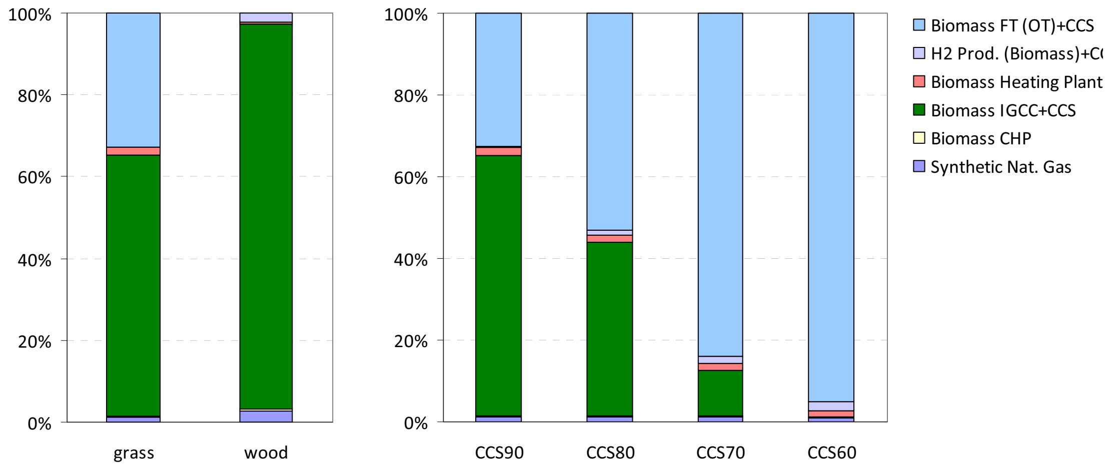

Figure 4: Competing biomass technologies: shares of biomass primary energy consumption of technologies cumulated from 2005-2100. Left: Fuel switch from grass to wood. Right: Variation of BIGCC capture rate.

4. Conclusion and Outlook

Results indicate that BioIGCC with CCS could serve as an important mitigation option and that it could even be the main bioenergy conversion technology as it efficiently provides negative emissions and produces electricity. Future techno-economic studies and demonstration plants of the BIGCC+CCS process should focus on the more challenging biomass raw material grass instead of wood as it can be produced at lower costs and enables high amounts of negative emissions in case of good techno-economic performance of the process. The capability of producing negative emissions decides on the application of BIGCC+CCS as a mitigation technology. Given a high capture rate, BIGCC+CCS can significantly contribute to mitigation of the energy system emissions. All considered scenarios show high cumulated amounts of captured carbon that range from 130 GtC to 240 GtC. In case of expensive lignocellulosic biomass raw material BIGCC+CCS with a high capture rate turns out to be the preferred bioenergy conversion technology. The overall primary energy consumption of biomass reacts much more sensitive to price changes of the biomass than to techno-economic performance of the BIGCC.

As biomass production and demand do not coincide in identical world regions we will couple regionalized models with regions linked by biomass trade. Moreover the new HTC technology (HTC = hydrothermal carbonisation) will be assessed [24]. The product of the HTC process is similar to charcoal and thus is expected to be appropriate for various alternative downstream applications like fuel or electricity production (with CCS). It could also be used for soil improvement and thus could serve as a simple carbon sink provided it is kept in the soil for a long time. Besides that it can be used as source material for chemical processes. As HTC is a densification process of biomass raw material it may facilitate long-distance transport of biomass.

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