Achieving negative emissions in the power sector: A technological and regional approach with TIAM-FR

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Abstract

It seems increasingly likely that atmospheric greenhouse gases concentration will overshoot the recommended 400 ppm_{C02} target. Therefore, it may become necessary to use bioenergy with carbon capture and storage technologies (BECCS) to remove CO_2 from the atmosphere. This study evaluates the possible deployment of BECCS in the power sector using the bottom-up multiregional optimization model TIAM-FR. The results of this long-term modeling exercise suggest that, to achieve a stringent target, BECCS technology represents an environmentally and economically viable option. The regional analysis shows that industrialized countries will develop CCS mainly on biomass sources while CCS on fossil fuel will be widely deployed in fast-developing countries.

Keywords

Bioenergies, Carbon capture and storage, Long term modeling, Electricity, Environmental policies

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1. Introduction

In its Fourth Assessment Report, the IPCC showed that in order to limit the long-term global temperature increase to 2°C above pre-industrial levels and avoid dangerous consequences of climate change, global greenhouse gas (GHG) emissions need to be reduced by 50% to 85% by 2050. However, it seems increasingly likely that we will overshoot this limit. The IEA, in its World Energy Outlook (2011), announces that "the door to 2°C is closing". Therefore, it may become necessary to develop technologies that capture emissions out of the atmosphere (negative CO_2 emissions technologies). By capturing CO_2 from the air (directly or indirectly), CO_2 emissions can be sequestered and the stock of atmospheric CO_2 reduced to correct for the overshoot. It could also be used to offset additional anthropogenic emissions from sectors where emissions reductions are difficult to obtain or uneconomical, such as diffuse emissions. A range of negative emissions options have been identified, such as those that directly remove CO_2 from the atmosphere, so-called direct air-capture technologies (artificial trees and Lime-Soda process), and those that remove emissions indirectly (augmented ocean disposal processes; biochar and Bioenergy with Carbon Capture and Storage (BECCS)) (Mcglashan, 2012). The cost of direct air-capture technologies is still very uncertain (Keith, 2009) therefore BECCS appears to be the negative CO_2 emissions technology with the most immediate potential to reduce emissions. It can be defined as a process in which CO_2 originating from biomass is captured and stored in geological formations. Biomass absorbs CO_2 from the atmosphere through the process of photosynthesis and releases it during transformation or combustion. If the released CO_2 could be captured and stored permanently in geological storage sites, then we would have a situation of negative CO_2 emissions given sustainable biomass harvesting practices.

Many empirical studies show that the use of BECCS is increasingly significant to tackle strict stabilization targets (Fischer *et al.*, 2007, Clarke *et al.*, 2009; Azar *et al.*, 2006, 2010; Edenhofer *et al.*, 2010; Katofsky *et al.*, 2010; Luckow *et al.*, 2010; van Vuuren *et al.*, 2007, 2010b; van den Broek *et al.*, 2011; Lemoine *et al.*, 2012). The availability of BECCS decreases the cost of meeting low stabilization targets. By comparing the results of three energy models that include BECCS technologies, Azar *et al.* (2010) show that CO_2 atmospheric concentration can be reduced by 50-100 ppm for the same cost when BECCS is used. In fact, negative emissions are essential to meet low concentration targets, but the introduction of BECCS also diverts the emission reduction pathway toward the long-term atmospheric concentration target. It increases near-term flexibility in abatement timing in such a way that emissions reduction occurs in the second half of the century, and modest emissions reduction can be achieved before decreasing the total discounted abatement cost (van Vuuren *et al.*, 2010b; Azar *et al.*, 2010, Clarke *al.*, 2009). However, this argument to postpone emissions reduction raises serious concerns, since relaxing action today could lead to a high overshoot in the concentration level with irreversible consequences on the climate (Azar *et al.*, 2010). Several sectors have been identified as appropriate targets for the BECCS option, such as the heat and pulp mill industries (Hektor and Berntsson, 2007; Möllersten *et al.*, 2006), the biofuel sector (Möllersten *et al.*, 2003; Kheshgi and Prince, 2005; Mathews, 2008; Lindfeldt and Westermark, 2008, 2009, Laude *et al.*, 2011) and the electricity sector (Carpentieri *et al.*, 2005; Rhodes and Keith, 2005; Uddin and Barreto, 2007). This study focuses on the electricity sector, which is the main producer of energy-related CO_2 emissions. CO_2 capture and storage technologies have therefore been recognized as critical factors to decarbonize this sector (Ricci and Selosse, 2011). Indeed, the majority of support for CCS demonstrations has focused on power applications (IEA, 2012).

We contribute to the growing body of literature on BECCS by introducing a wide variety of CCS technologies on coal, gas, co-combustion of coal and biomass and biomass power plants in TIAM-FR. This bottom-up optimization model provides a technology-rich basis for estimating energy evolution and structural changes in the long term. It depicts the energy system over the period 2005-2100 in such a way as to minimize the net total cost of the system under a number of environmental, technological and demand constraints. The aim of this paper is to assess the deployment of BECCS technologies in the electricity sector, up to 2100, under ambitious climate objectives. A regional analysis is conducted in order to quantify BECCS potential in industrialized, fast-developing and developing countries. Moreover, the feasibility of BECCS as a negative emissions process technology is heavily dependent on the future development of carbon capture and storage technology. Due to substantial uncertainties regarding storage capacities, availability of CO_2 transport networks, social acceptability, legal issues, and adequate technology incentives (Herzog, 2011), we also investigate the impact of exogenous constraints on CCS and BECCS availability on the electricity mix structure and on the total cost of the energy system.

The paper is organized as follows: Section 2 describes the model and the main assumptions. Section 3 presents and discusses the results of the long-term modeling. The final section gives some concluding remarks.

2. TIAM-FR model and scenarios

2.1. TIAM-FR structure

Analyses carried out in this paper are based on the TIAM-FR model developed by the MINES ParisTech Center for Applied Mathematics. TIAM-FR is the French version of the TIMES Integrated Assessment Model, a widely used, linear programming TIMES family model developed under the IEA's Energy Technology Systems Analysis Program (ETSAP) (Loulou and Labriet, 2008). TIAM-FR is a bottom-up optimization model that offers a technology-rich representation of the energy system. The development of the energy system can be analyzed in short-, medium- and long term perspectives up until the year 2100. TIAM-FR is geographically integrated in 15 global regions that are presented in the following table.

Table 1: Regions in TIAM-FR model

Regions group	Regions
Industrialized countries	Australia-New Zealand (AUS), Canada (CAN), United-States of America (USA), Western Europe (EU-15, Iceland, Malta, Norway and Switzerland, WEU), Eastern Europe (EEU), Japan (JPN)
Fast developing countries	India (IND), China (includes Hong Kong excludes Chinese Taipei, CHI)
Developing countries	Africa (AFR), Central and South America (CSA), Middle-East (includes Turkey, MEA), Mexico (MEX), South-Korea (SKO), Other developing Asian countries (includes Chinese Taipei and Pacific Islands, ODA), Former Soviet Union (include the Baltic states, FSU)

TIAM-FR is a linear-programming approach in which the technical optimum is computed by minimizing the discounted global system cost. For each region, it computes a total net present value of the stream of annual costs, discounted to a selected reference year. These regional discounted costs are then aggregated into a single total cost which is the objective function to be minimized by the model while satisfying a number of technological and/or environmental constraints. The objective function is:

$$NPV = \sum_{r=1}^{R} \sum_{y \in years} (1 + d_{r,y})^{refy-y} * ANNcost(r, y)$$

where *NPV* is the net present value of the total cost; *ANNcost(r,y)* is the total annual cost in region r and in year y; $d_{r,y}$ is the discount rate, *refy* is the reference year for discounting, *years* is the set of years and *R* the set of regions (Loulou, 2008).

Each step of the energy chain, from mining to final energy service demands (heating, lighting, travel, etc.), is identified in the model in terms of both economic and technical characteristics. Technologies to achieve these stages are called processes (extraction of fossil fuels, imports, processing of primary energy in final energy, etc.). Energy carriers (primary energy, final energy, and useful energy), energy services, materials, cash flows and emissions are called commodities. The links between the commodities and processes are represented in a Reference Energy System. Each primary energy form is extracted from multiple layers of either reserves (fossil, biomass) or resource potential (wing, hydro, geothermal, etc.), each with a potential and a specific unit cost. This constitutes a supply curve for each energy form. Some types of energy are endogenously traded between the 15 regions (coal, crude oil, refined petroleum products, natural gas, and liquefied natural gas). The costs of these energy forms are therefore endogenous. This is not the case for biomass. In the model, biomass is characterized by manifold sources - industrial waste, municipal waste, landfill gas, bioenergy crops, and solid biomass resources – and the fact that it is not traded between regions. The maximum amount of available biomass for each region is determined exogenously according to IEA data. The global potential is estimated at 234 EJ per year in 2050 (72 EJ come from bioenergy crops, 72 EJ from solid biomass resources and the rest from industrial waste, municipal waste and landfill gas). In literature, biomass potential varies greatly given the different assumptions on land use, yield development, food consumption and other criteria of sustainability, such as water scarcity and loss in biodiversity. This potential varies from 100 EJ to 300 EJ per year by 2050 (van Vuuren *et al.*, 2009, IPCC, 2011). Electricity is produced by a large number of technologies that use one or more primary resources as inputs. The energy demand determinants, such as population and gross domestic product growth rates, as well as the evolution of demand sectors, are mainly taken from IEA, United Nations and FAO. The latest calibration of the model drivers is based on data from the Energy Technology Perspectives in 2010 (IEA, 2010). Through its integrated climate module, the model makes it possible to analyze and make assumptions on atmospheric GHG concentrations and temperature changes. It integrates CO_2, CH_4 and N_2O emissions from each fuel combustion and process.

2.2. CCS and BECCS in TIAM-FR

TIAM-FR integrates several carbon capture and sequestration technologies on fossil or bioenergy resources. The purpose of the capture process is to obtain a concentrated stream of almost pure CO_2 at high pressure. There are three modes of capturing CO_2 from fossil fuels (coal, oil, natural gas) in the model: 1) a post-combustion mode using a variety of processes such as reactive absorption or membranes, 2) a pre-combustion mode with conversion of fuel-chemical energy into H_2, followed by simultaneous low-cost carbon separation and 3) an oxy-combustion mode characterized by the low cost of CO_2 separation, but necessitating a supply of O_2. For bio-plants and co-firing plants (co-combustion of biomass and fossil fuel), two capture technologies are retained: pre-combustion capture for the biomass gasification process, and post-combustion capture for the biomass direct combustion process. For each technology, economic parameters must be completed, such as capital costs incurred for investing and dismantling processes, operation and maintenance costs, and the date the technology will enter the market (see cost details in table 2).

Table 2: BECCS and co-firing technologies in TIAM-FR

Technologies	**Inputs**	**Capture technology (capture rate 90%)**	**Year**	**$CAPEX_{2000}$ ($/kWe)**	**$OPEX_{2000}$ ($/kWe/a)**
Bio combustion plant	Solid biomass, Crop (100%)		2010	1700	63
Bio combustion plant with CCS	Solid biomass, Crop (100%)	Post-combustion	2020	2125	63
Bio gasification plant	Solid biomass, Crop (100%)		2010	2000	79
Bio gasification plant with CCS	Solid biomass, Crop (100%)	Pre-combustion	2020	2420	79
Co-combustion plant	Bio (20%) + Coal		2010	1300	52
Co-combustion plant with CCS	Bio (20%) + Coal	Post-combustion	2020	1650	64
Co-gasification plant	Bio (20%) + Coal		2010	1450	58
Co-gasification plant with CCS	Bio (20%) + Coal	Pre-combustion	2020	1800	70

Storage capacities are indicated by region in the TIAM-FR model. Global cumulated storage capacities are 14,800 Gt of CO_2 of which 12,600 Gt of CO_2 can be stored in deep saline aquifers (appendix 1).

In order to evaluate the role of BECCS in long-term climate scenarios, we make different assumptions on the stringency of the environmental policy.

2.3. Climate scenarios

Three climate scenarios are assumed at a global level.

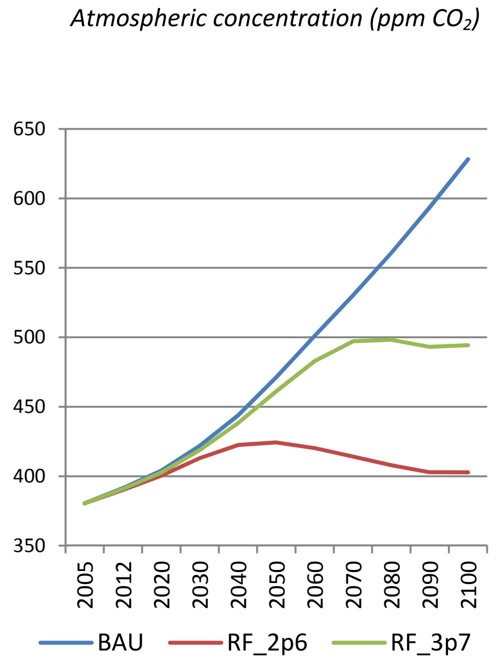
- *BAU scenario:* A baseline scenario with no emission constraint is calculated first. This *Business As Usual* (*BAU*) scenario outlines some key patterns in the evolution of the energy system, and serves as the starting point for the analysis. The *BAU* scenario is then compared to the emissions reduction policy scenarios to assess the implications of carbon constraints on the evolution of the electricity system and formulate policy recommendations. The CO_2 emissions total will increase significantly in the BAU scenario, that is, from about 25 Gt in 2005 to 75 Gt by 2100. Driven by these increased emissions, CO_2 atmospheric concentration will rise significantly over time and reach 628 ppm in 2100, which corresponds to a radiative forcing of about 5.4 W/m^2 during the same period.

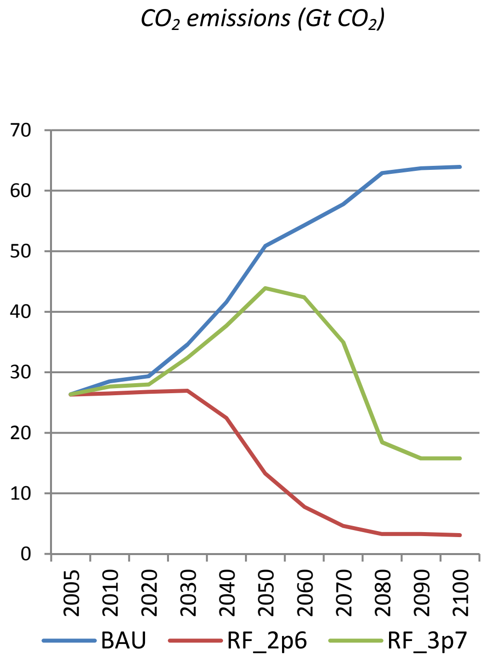
- *RF_2p6 scenario:* This scenario consists in limiting radiative forcing to 2.6 W/m^2 by 2100. This objective is compatible with the UNFCCC consensual 2-2.4°C objective (as specified by IPCC). In TIAM-FR, global CO_2 emissions decrease by 50 % in 2050 and by 84% in 2100 compared to the model's reference year of 2005. It allows the atmospheric CO_2 concentration to stabilize at 424 ppm by 2050 and 402 ppm by the end of the century (figure 2).

- *RF_3p7 scenario:* This scenario limits radiative forcing to 3.7 W/m^2 by 2100. CO_2 emissions increase by 66.5% from 2005 to 2050 and reach their highest level in 2050 (43.9 Gt of CO_2). Then emissions decrease in the second part of the century and reach 15.7 Gt of CO_2 in 2100, a reduction of 40% compared to 2005 (figure 1). The atmospheric concentration pursues its growth until 2080 and then slows down to reach 493 ppm in 2100**.**

In both climate scenarios, emissions in the electricity sector are divided by 7 during the overall period to meet the global objective. In scenario *RF_3p7* emissions rise from 2005 to 2050 and then decrease sharply, while in scenario *RF_2p6*, emissions decline from 2010 and then level off in the second part of the century.

Figure 1: Resulting atmospheric concentration (ppm CO_2) and CO_2 emissions (Gt CO_2)





3. Results: Assessing CCS and BECCS deployment in the electricity sector

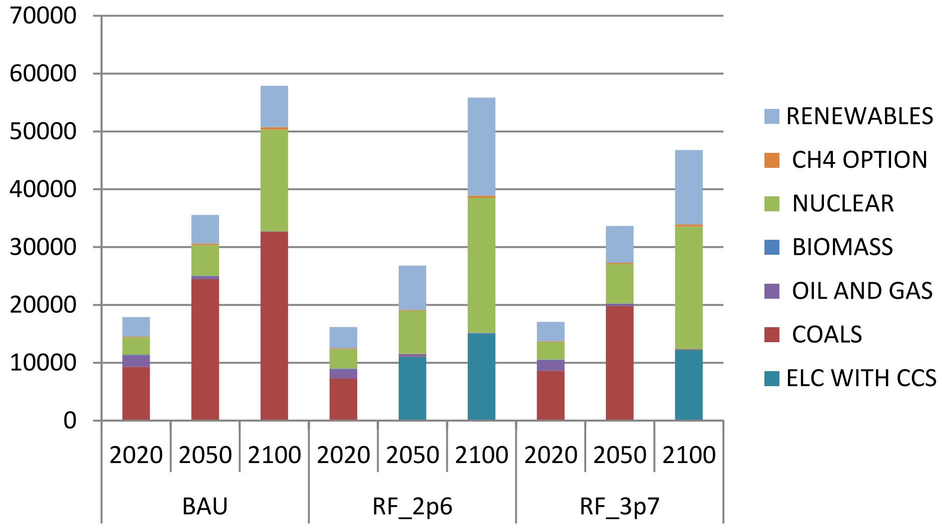
3.1. Impact of climate policies on the electricity mix and CCS deployment

In the *BAU* scenario, electricity generation increases from 17,934 TWh in 2005 to 35,560 TWh in 2050 and 57,900 TWh in 2100. The implementation of a carbon policy induces a change in the structure of the electricity mix and the wide deployment of carbon capture and storage technologies from 2030 in *RF_2p6*, and from 2070 in the less stringent scenario *RF_3p7*.

In *RF_2p6*, in 2050, electricity from coal, gas and biomass plants with carbon capture and storage represents 41% of the mix, with nuclear and renewables accounting for 28% each. In 2050, 99% of biomass power plants, 97% of coal power plants, and 82% of gas power plants are equipped with CCS technology. In 2100, there is significant deployment of renewables and nuclear energy. Electricity generated from nuclear and renewables multiplies by respectively 7 and 4.5 between 2020 and 2100.

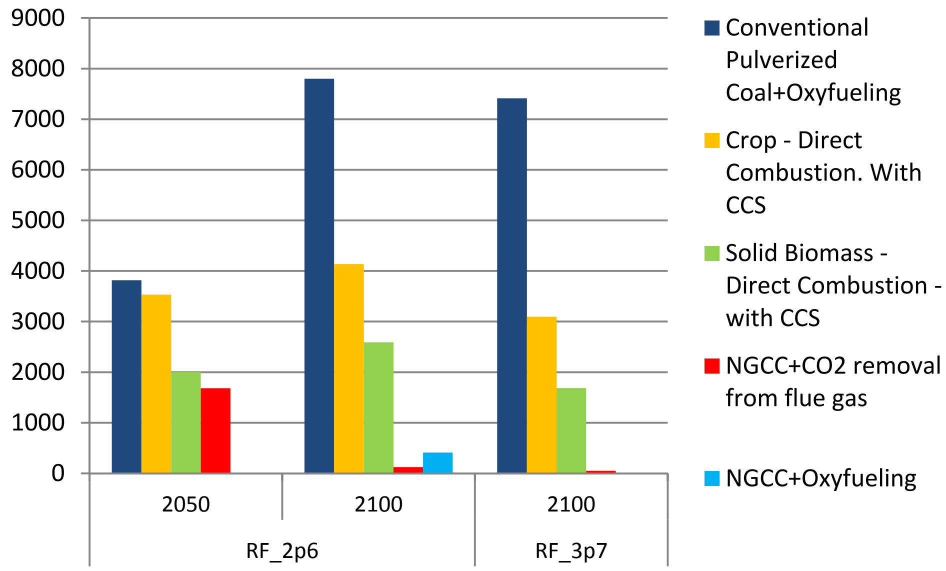
In *RF_3p7*, in 2050, coal remains the principal energy used in electricity production. It represents 59% of the mix, nuclear accounts for 20% and renewables for 27%. In 2100, 26% of electricity is produced with CCS, 45% with nuclear and 27% with renewables. Figure 2 describes the electricity mix evolution from 2020 to 2100 in view of the two climate scenarios investigated.

Figure 2: World electricity production (TWh)



The following graph focuses on the CCS technologies developed under the two climate policies. CCS on coal and biomass power plants become competitive options in 2030 in *RF_2p6* and in 2070 in *RF_3p7*. CCS on gas power plants enters the market in 2040 in *RF_2p6* and only in 2090 in *RF_3p7*.

Figure 3: World electricity production from CCS technologies (TWh)



The results show the role CCS plays in the electricity mix. In *RF_2p6*, 1,647 TWh, 11,038 TWh and 15,062 TWh of electricity are produced with a CCS technology in respectively 2030, 2050 and 2100. The average annual growth rate over this period is 3%. In 2050, 50% of CCS technologies are applied to fossil resource power plants (coal (35%) and gas (15%)) and 50% to solid and crop biomass power plants. The share of fossil fuel power plants with CCS out of the total CCS deployment increases from 2050 to 2100, rising from 50% in 2050 to 55% in 2100. 4.8 Gt of CO_2 are captured and stored in geological formations in 2050 and 12 Gt in 2100 in *RF_2p6*. In *RF_3p7*, electricity produced with CCS reaches 12,244 TWh in 2100 and 8 Gt are captured per year in the same period. 61% of technologies are applied to coal power plants and 39% to biomass power plants.

The next section evaluates the impact of the availability of CCS, BECCS and co-firing technologies on the electricity mix and on CCS technology deployment in the most stringent scenario *(RF_2p6)*.

3.2. A Technology availability analysis in a climate constrained economy

The technology scenarios are the following:

- *RF_2p6_NoCCS:* CCS seems to be a promising technology to reduce CO_2 emissions but a significant number of uncertainties and key aspects need to be addressed to scale up this technology. Therefore, we consider the case where CCS is not deployed on any type of power plant throughout the time horizon.
- *RF_2p6_NoBECCS*: We assume that CCS technology on full biomass power plants is not available. It is only developed on coal, gas, and co-combustion of coal and biomass power plants.
- *RF_2p6_NoBECCSCF:* Finally, we assume that CCS is only developed on coal and gas power plants. BECCS and CCS are not available on co-firing technologies.

Table 3 and figure 4 show the structure of the electricity mix for 2050 and 2100 and the deployment of CCS under the technology scenarios for the climate scenario (*RF_2p6)*.

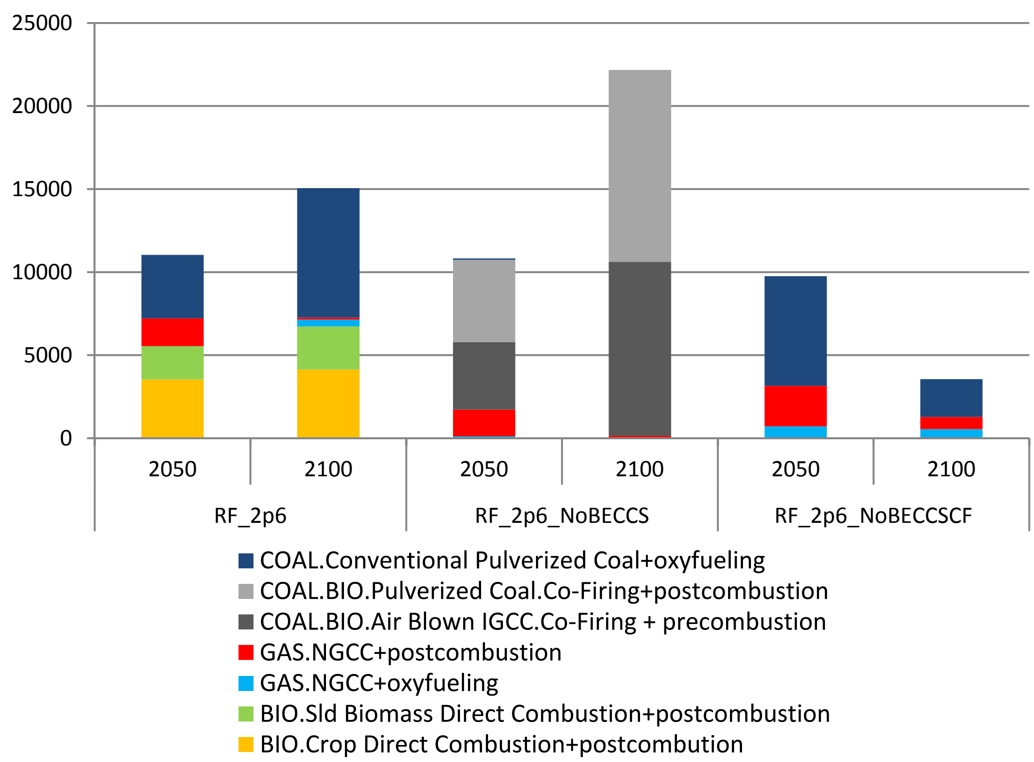
Table 3: World electricity mix in percent (%)

2050	RF_2p6	RF_2p6_NoCCS	RF_2p6_NoBECCS	RF_2p6_NoBECCSCF
ELC FROM COALS	0.4	0.3	0,1	0.1
ELC FROM OIL & GAS	1.4	1.3	0.9	1
ELC FROM NUCLEAR	28	41.7	29	20
ELC FROM BIOMASS	0.1	0.2	0.2	0.2
ELC FROM RENEWABLES	29	54	29	30
ELC WITH CARBON CAPTURE	41	0	40	38

2100	RF_2p6	RF_2p6_NoCCS	RF_2p6_NoBECCS	RF_2p6_NoBECCSCF
ELC FROM COALS	0	0.8	0.2	0.2
ELC FROM OIL & GAS	0	0.2	0	0
ELC FROM NUCLEAR	42	50	37	49
ELC FROM BIOMASS	0.2	0.4	0.2	0.4
ELC FROM RENEWABLES	30	48	28	42
ELC WITH CARBON CAPTURE	27	0	35	7

When CCS technologies are not available (*RF_2p6_NoCCS*) the environmental objective is achieved by the rapid deployment of renewable energies and the increase in the nuclear share.
In 2050, the fact that biomass-CCS technology is not available does not change the structure of the electricity mix. In *RF_2p6* and *RF_2p6_NoBECCS*, the contribution of CCS is about 40% of the electricity mix. In *RF_2p6*, we can see that the technology is applied at 50% on both biomass and fossil power plants (figure 3). When BECCS is not available there is a switch from biomass plants to mainly co-firing plants (figure 4). However, in 2100, comparing *RF_2p6* and *RF_2p6_NoBECCS*, the CCS share in the power mix increases. Electricity produced from CCS rises from 15,062 TWh in *RF_2p6* to 22,169 TWh in *RF_2p6_NoBECCS*. In this last scenario, CCS is applied to pulverized coal and air-blown IGCC co-firing plants (figure 4).

Figure 4: World electricity production from CCS technologies (TWh)

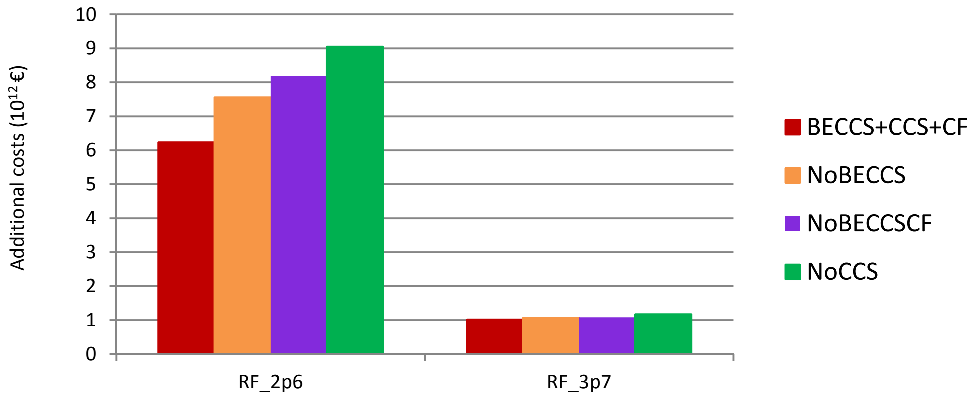


When neither CCS on biomass nor CCS on co-firing power plants are available (*RF_2p6_NoBECCSCF*), the CCS share in the mix, compared to its share in scenario *RF_2p6*, decreases slightly in 2050 (-11%) and considerably in 2100 (-76%). In 2100, 15,060 TWh of electricity is produced with a CCS technology in *RF_2p6* compared to only 3,550 TWh in *RF_2p6_NoBECCSCF*. This decrease is mainly compensated by an increase of renewable and nuclear energies. Why does CCS on coal and gas power plants not act as a substitute for BECCS and co-firing technologies? CCS on coal and gas is penalized under a stringent emissions reduction scenario because it does not allow a zero rate of CO_2 emissions compared to totally carbon-free technologies, such as renewables and nuclear.

Co-firing option appears to be a good solution to meet the climate target when CCS on bio plants is not available, notably IGCC power plants. IGCC systems are one of the most efficient clean-coal power production technologies. They have the advantage of processing many kinds of feedstock, such as coal, coke, residual oil, biomass and municipal waste. In IGCC plants, feedstock is converted into a hydrogen-rich syngas that is cleaned and burned in a gas turbine. The exhaust gas in then used to power a steam turbine; when CCS is applied, the syngas is transported to a shift reactor to convert CO into CO_2 and hydrogen H_2. The CO_2 produced is highly concentrated and can therefore be removed by physical absorbents with low efficiency penalties and at a low cost. In principle, IGCC technology is the cheapest option for CCS (IEA-ETSAP, 2010). However IGCC plants are more expensive and less reliable than supercritical conventional pulverized coal power plants (in the model about 15% more expensive). There is no consensus on which option will cost the least in the future. In the model, the cost of the plants with capture is fairly similar for both technologies. In figure 4, we can see that NGCC power plants with CCS also play a role in CCS deployment. NGCC is a mature technology. It was first introduced in the 1990s. Since then, the technology has made progress with cooling and materials development. As a result, efficiency has now reached 60% on a lower heating value basis, compared to standard gas-fired power plants in 2003, when the average efficiency was around 42%. NGCC emits less than half as much CO_2 as coal-fired power plants per unit of electricity, making it an interesting option when co-firing and BECCS technologies are not available (*RF_2p6_NoBECCSCF*). The constraint on the availability of negative emissions technologies affects the evolution of the electricity mix structure. What, then, is its impact on the total cost of the energy system?

Figure 5 presents the cost of the different stabilization and technological scenarios. It is expressed as the net present value cost of additional mitigation expenditure compared to the BAU scenario (2005-2100) discounted at 5% in trillions of $€_{2000}$.

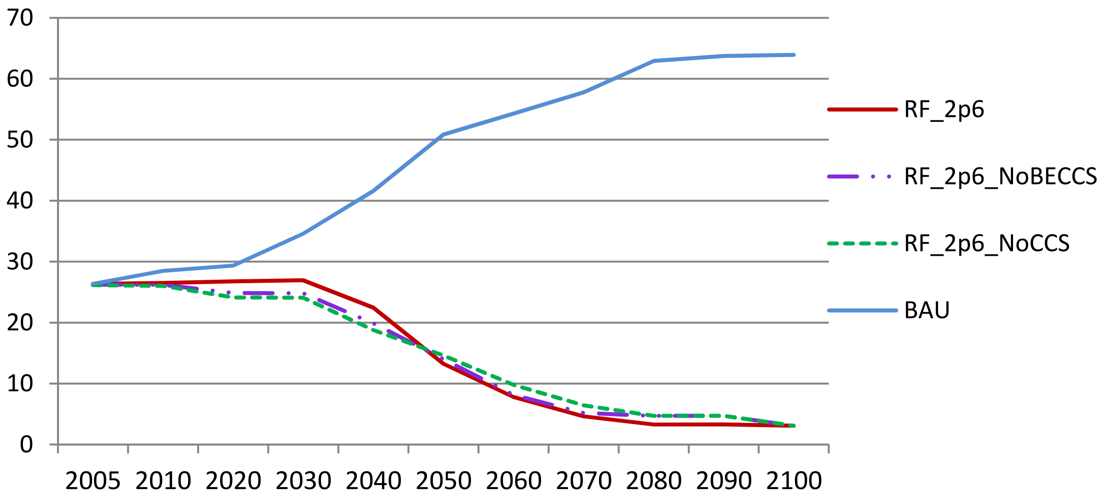
Figure 5: Net present value costs for the climate scenarios by 2100



It can be seen that the option of using BECCS reduces the cost of meeting the *RF_2p6* stabilization target. We can expect that the lower the stabilization target, the more significant the BECCS contribution will be to reducing costs as negative emissions become critical. In line with literature, we show that the availability of BECCS also has an impact on the least-cost emission reduction pathway towards the long-term concentration objective (Clarke *et al.*, 2009; Azar *et al.*, 2010; van Vuuren *et al.*, 2010b). Conversely, in the *RF_3p7* scenario, the total discounted cost of the energy system for achieving the carbon target does not change much, whatever the CCS technology availability. Note however a higher additional cost in case of the total unavailability of CCS. Low carbon transition tends to be based more on other clean technologies.

The availability of BECCS in *RF_2p6* increases flexibility in timing and postpones emission reduction after 2030. The CO_2 emission peak is around 2030 and then stringent abatement occurs between 2030 and 2050 (scenario *RF_2p6)* whereas, when BECCS is unavailable, CO_2 emissions steadily decrease from 2010 (figure 6).

Figure 6: CO_2 emissions pathway ($GtCO_2$) when BECCS and CCS technologies are not available (RF_2p6 scenario)



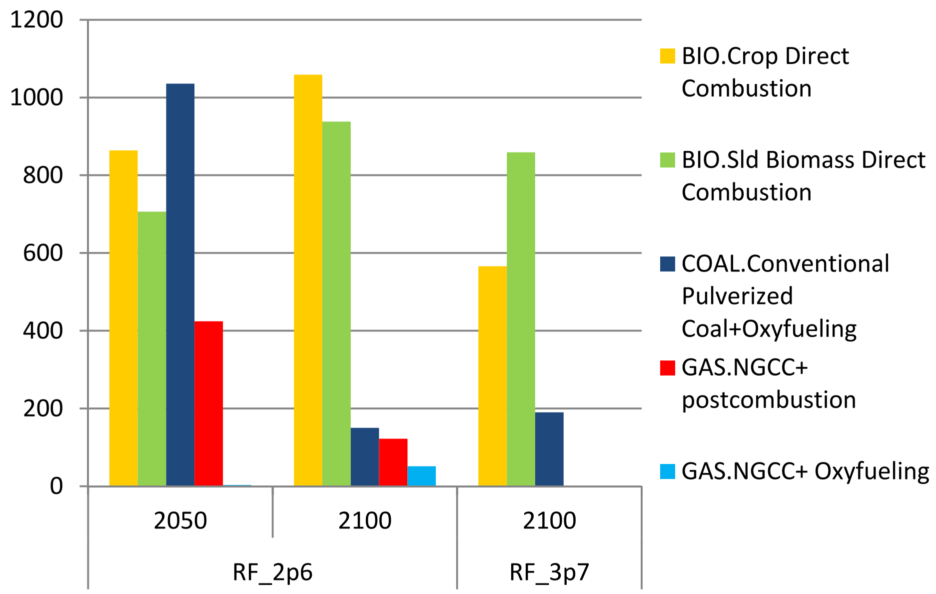
We conduct a regional study to quantify BECCS potential in industrialized, fast-developing and developing countries

3.3 A regional analysis

3.3.1. CCS deployment in industrialized countries

In scenario *RF_2p6*, CCS enters the market in 2030 in industrialized countries on both conventional pulverized coal power plants and solid biomass direct combustion. Electricity from plants with carbon capture and storage increases by 20% per year between 2030 and 2050. It peaks in 2070 and then decreases over time (it is mainly the share of coal and gas + CCS that decreases) (figure 7). Given the progressively stringent climate obligations, the low but not nil CO_2 emissions rate of coal and gas + CCS is compensated by the increase of BECCS and other totally carbon-free technologies, such as nuclear. In 2100, 1.9 Gt and 1.7 Gt of CO_2 are captured and stored per year respectively in *RF_2p6* and *RF_3p7*.

Figure 7: Electricity production from CCS technologies (TWh) in industrialized countries

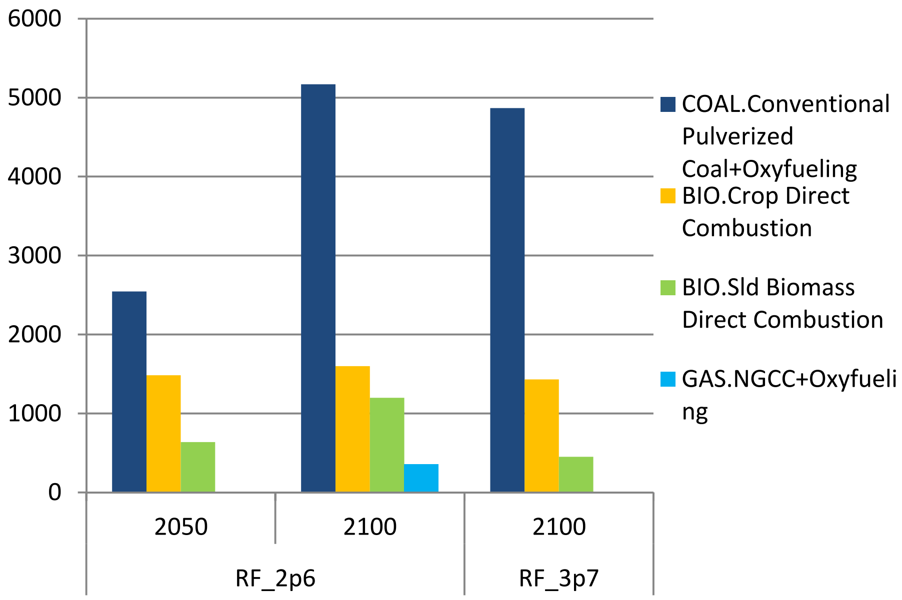


In industrialized countries, CCS is mainly applied to biomass power plants after 2050 to satisfy both environmental constraints. In *RF_2p6*, 51% of the deployed CCS is applied to bio plants (1,570 TWh) in 2050; this share increases and reaches 86% in 2100. In Europe (WEU+EEU) and in the USA, CCS on bio plants represents 35% and 55% respectively of total CCS deployment in 2050, and more than 80% in 2100. Australia, Canada and Japan only develop CCS on bio plants to meet the global objective. In *RF_3p7*, in 2100, CCS is also essentially applied to bio plants (1,425 TWh of electricity produced from biomass comes from a plant equipped with CCS).

3.1.2 CCS deployment in fast-developing countries

In fast-developing countries, the CCS power share of electricity production is multiplied by almost 3 from 2030 to 2050 and by 1.7 from 2050 to 2100 in *RF_2p6*, rising from 1,557 TWh in 2030 to 4,667 TWh in 2050 and 8,330 TWh in 2100 (figure 8). In *RF_2p6*, 54% of CCS is applied to fossil power plants in 2050 and 66% in 2100. In the less stringent scenario, CCS is deployed at 72% on coal power plants. CCS is mainly developed on coal power in China, where it represents more than 70% of the total deployment in both scenarios, whereas India relies more on BECCS than on fossil CCS. About 5 Gt of CO_2 are captured and stored in India and China in 2100.

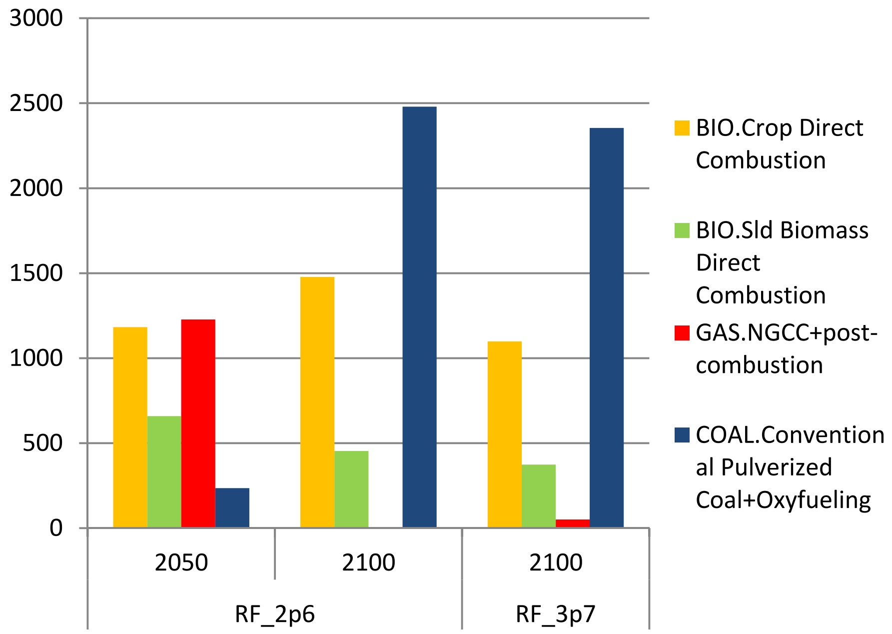
Figure 8: Electricity production from CCS technologies (TWh) in fast-developing countries



3.1.3 CCS deployment in developing countries

In 2050, half of the CCS deployed is applied to bio plants, and in 2100 CCS is more developed on fossil resources in developing countries (figure 9). However, differences exist between countries. Africa, South America and Central America rely solely on BECCS, while in the Middle East and the former Soviet Union, CCS is mainly used on gas-fired power plants by 2050 and coal plants in 2100. Countries in South East Asia rely primarily on BECCS and a little on gas-fired plants + CCS by 2050. Developing countries store 3 Gt of CO_2 in geological formations by the end of the century in the most stringent scenario.

Figure 9: Electricity production from CCS technologies (TWh) in developing countries



4. Conclusion

In this paper we focused on BECCS technology, which has been acknowledged as an interesting negative emission option for achieving major CO_2 emissions reductions. We therefore evaluated the role of power generation from bio plants with CCS to achieve a low climate target by 2100 using the optimization model TIAM-FR. We conducted a regional analysis to understand where the technology will be developed. We also studied what impact the unavailability of this technology would have on the structure of the electricity mix and the cost of the system.

Under a stringent climate control target, the model is favorable for the widespread deployment of CCS technologies in the power sector from 2030. 40% of the electricity generated in 2050 comes from plants equipped with CCS technology. At a global level, 50% of the CCS deployed is associated with bio plants and 50% with fossil plants, with a preponderance of coal power plants. It is important to keep in mind that the possible contribution of BECCS depends heavily on the potential and societal acceptance of bioenergy on one hand, and the deployment of capture and storage technologies on the other. Although there may be significant potential for this technology, uncertainties and concerns remain regarding technology development, carbon-negative life cycle assessment, food security, and biodiversity (van Vuuren *et al.*, 2010a). Therefore, this study also looked at what happens when BECCS is not available in the long run.

The results show that with a specific constraint on CCS diffusion, the share of renewables and nuclear energy becomes significant to meet the climate target. Moreover, co-firing options tend to be good substitute for CCS on bio plants when this last option in not available. But more importantly, if carbon-negative technologies (co-firing and BECCS) are not available, the share of CCS in the electricity mix significantly decreases in 2100. CCS on fossil fuel does not compensate for the absence of carbon-negative technologies as it is not a carbon-neutral technology.

In line with literature, our scenarios reveal that while a broad range of mitigation technologies are needed to attain low concentration targets, the availability of BECCS enhances the possibility of decreasing the cost of meeting those targets. The emissions reduction pathway depends strongly on technology assumptions. If negative emissions are available, less abatement takes place in the short term, and more aggressive action occurs later in time.

The regional analysis suggests that industrialized countries will develop CCS mainly on their bio plants, whereas in fast-developing countries, principally China, CCS will be applied to coal power plants. In developing countries, there are disparities between countries. Some will only develop BECCS, for instance: Africa, South and Central America and Japan, whereas the Middle East and the former Soviet Union will develop CCS on their gas power plants.

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Appendix 1. Cumulated storage capacities in GtCO2 assumed in TIAM-FR

Storage capacity	**AFR**	**AUS**	**CAN**	**CHI**	**CSA**	**EEU**	**FSU**	**IND**
Enhanced Oil Recovery	5.25	0	5	1.5	15	3	30	0
Depleted oil fields (onshore)	5.25	0	5	1.5	15	3	45	0
Depleted oil fields (offshore)	3	1.5	1	0.3	3	0	0	0
Depleted gas fields (onshore)	21	1.5	20	0	45	0	336	0
Depleted gas fields (offshore)	7.5	12	10	0	0	0	0	0
Enhanced Coalbed Methane Recovery <1000 m	3.75	37.5	25	75	0	15	75	7.5
Enhanced Coalbed Methane Recovery >1000 m	3.75	37.5	25	75	0	15	75	7.5
Deep saline aquifers	1.500	750	1.000	750	1.500	375	1.500	750

Storage capacity	**JPN**	**MEA**	**MEX**	**ODA**	**SKO**	**USA**	**WEU**	**World**
Enhanced Oil Recovery	0	75	0.75	2.25	0	15	0.75	153.5
Depleted oil fields (onshore)	0	112.5	7.5	15	0	15	0.75	225.5
Depleted oil fields (offshore)	0	15	4.5	2.25	0	15	6	51.55
Depleted gas fields (onshore)	0	300	15	45	0	15	22.5	821
Depleted gas fields (offshore)	0	75	15	30	0	15	45	209.5
Enhanced Coalbed Methane Recovery <1000 m	0	0	0	37.5	0	60	22.5	358.75
Enhanced Coalbed Methane Recovery >1000 m	0	0	0	37.5	0	60	22.5	358.75
Deep saline aquifers	7.5	750	375	1.500	15	1.500	375	12.648

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