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TOWARDS FOSSIL-BASED ELECTRICITY SYSTEMS WITH INTEGRATED CO_2 CAPTURE: IMPLICATIONS OF AN ILLUSTRATIVE LONG-TERM TECHNOLOGY POLICY[‡]

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Abstract

This paper examines the role of fossil-fired power plants equipped with carbon capture systems in a long-term scenario of the global energy system. Within this framework, the impacts of a technology policy is illustrated that requires over time an increasing fraction of fossil-fired power generation to incorporate carbon capture technologies leading in the long run to a virtually carbon-free electricity sector. We examine the costs and the potential contribution that such a policy could offer in reducing global energy-related carbon dioxide emissions and highlight some of the technologies that may play a key role in doing so. The analysis is carried out with the energy-systems optimization model MESSAGE considering endogenous technological learning for carbon capture technologies, such that they experience cost reductions as a function of accumulated capacity installations. In the context of a world where fossil-based power systems face pressure to evolve into cleaner configurations in the long term, coal-fired Integrated Gasification Combined-Cycle (IGCC) plants and gas-fired Combined-Cycle (NGCC) plants emerge as flexible, complementary technology choices that, while being attractive for electricity generation, could allow an efficient and cost-effective capture of carbon.

Introduction

Hedging against the risks of climate change requires significant and long-term structural changes of the global electricity generation, transmission and distribution systems, as well as the institutions and markets associated with them [1, 2]. An obstacle for achieving this goal in the short term is the large inertia of the energy system, due to the long lifetimes of its infrastructure. Fossil power plants are bound to continue playing a significant role in meeting the increasing global electricity demand well into the future. Hence, even under moderate growth assumptions for energy demand, global carbon dioxide emissions are expected to rise over the next decades [3, 4]. Technologies are required, which are capable of "bridging" the long-term transformation of today's energy system into a less carbon intensive one, while minimizing the environmental impacts during the transition period. Carbon removal and storage technologies appear to have a promising potential, since these technologies can be added to existing fossil infrastructure permitting a relatively rapid introduction compared to other clean and advanced alternatives.

The utilization of carbon capture and sequestration technologies is associated with additional costs and efficiency losses for energy conversion processes (compared to unabated energy production). Clearly, the large-scale deployment of these technologies will just occur if international climate policies are in place, which would give carbon an economic value, and hence, create an incentive for investments into emissions mitigation. In our scenario analysis, we assume ex-ante that international regulatory regimes would become effective, which lead to the introduction of a technology policy for carbon capture systems in the electricity sector. We do not assume any additional carbon mitigation measures for other sectors (or any carbon tax), since we want to primarily analyze the implications of the technology policy as a tool to foster the innovation and learning process for carbon capture systems.[1] In that sense, our scenario should be regarded as an attempt to address the questions: (1) "what-if" a

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[1] For multi-sectoral mitigation analysis focusing on carbon capture in the context of specific climate targets (e.g., stabilization of atmospheric carbon concentrations at 550 ppmv) see e.g., [5].

technology policy is introduced for carbon capture in the electricity sector that aims at the early and rapid diffusion of these technologies, (2) what are the costs of such a policy, (3) which power generation technologies would play a key role under the policy, and (4) how effective would such a policy be in reducing global carbon dioxide emissions?

The remainder of this paper is organized as follows. Section 2 briefly describes carbon capture technologies in the power sector. Section 3 presents the main model and scenario assumptions, focusing on the CCS policy and the technical and economic characteristics for carbon capture and storage technologies. The scenario quantification and results are presented in Section 4. Finally, Section 5 presents conclusions and policy implications from our analysis.

Carbon capture in fossil power plants

The separation and capture of CO_2 in fossil-fired power plants can be made either before or after the combustion process, using chemical or physical solvents or membranes. Post-combustion capture refers to the separation of CO_2 from the stream of flue gases resulting from fossil fuel combustion. In the conventional air-based combustion, the resulting concentration of CO_2 in the flue gas stream is low, making the process of separation very laborious. As alternatives, oxygen-based combustion and O_2/CO_2 cycles have been proposed. In pre-combustion capture, the fossil fuel is decarbonized, i.e. its carbon content is removed, before it is used for electricity generation. This is typically achieved by producing a synthesis gas (syngas), consisting mainly of hydrogen and carbon monoxide, from which a concentrated stream of CO_2 can be separated [6].

Post-combustion capture technologies can be applied to conventional fossil-fired power plants. Pre-combustion capture, however, requires new designs of technologies that may operate with hydrogen-rich syngases. Thus, the latter needs an adaptation and re-design of current technologies, such as natural gas combined-cycle (NGCC) turbines [7], or the introduction of advanced technologies, such as integrated gasification combined-cycle (IGCC) plants, high temperature fuel cells or a hybrid system combining both of them.

It is likely that carbon capture technologies would be initially introduced as an "add-on" technology for conventional fossil-based power technologies, thus favoring the conventional post-combustion approach. Later on, as new types of enhanced power generation technologies gain significant market shares, carbon capture could become a "built-in" feature. This would contribute to optimize the process from the conception and design stages of the power plant and would pave the way for advanced O_2/CO_2 cycles and pre-combustion capture approaches.

Main scenario assumptions

The evolution of the energy system, its direction and the associated emissions, are subject to large uncertainties, particularly if the analysis extends hundred years into the future, as in our case. The selection of the underlying input assumptions are decisive in obtaining plausible and representative conclusions. These assumptions specify, among others, the underlying population and economic trends, the development of energy demand, and the amounts of available primary energy resources. The scenarios presented here adopt the main input assumptions of the MESSAGE-A2 scenario developed for the IPCC-SRES [4]. A2 combines assumptions of high population with moderate economic growth and relatively slow technological change, leading to substantial increase in carbon emissions in the long run.[2] In our interpretation the massive penetration of CCS is most consistent with fossil-intensive scenarios that depict slow rates of technological change as portrayed by the A2 scenario. Slow technological change usually translates into delayed penetration of advanced and renewable technologies, leading (due to the path-dependency of the energy system) to the "lock-in" into fossil-based supply structures and higher needs for CCS. In our analysis we compare two main scenarios: (1) the A2 baseline scenario with (2) the A2-CCS scenario including the technology policy for carbon capture and storage. The underlying GDP and population

[2] The scenario quantification has been carried out with MESSAGE [8], a "bottom-up" systems-engineering optimization model of the energy system. The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. The model's current version, MESSAGE IV, provides global and sub-regional information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy.

assumptions are presented in Table 2. For a more detailed quantification of the A2 baseline see SRES [4]. Next we shall focus on the description of assumptions concerning carbon capture and storage, and the CCS policy that enforces their penetration.

An illustrative carbon capture technology policy

The CCS policy enforces an increasing share of fossil-fired power plants to use carbon capture technologies up to the point where in the very long term all fossil-based power plants are equipped with CCS. Consistent with historical patterns of technology diffusion, we assume that the adoption of technological innovation experiences a time delay between regions belonging to the "innovation core" and regions in the periphery of the spatial diffusion domain [9]. We assume that the industrialized world operates as the core of the diffusion process and specify two different logistic penetration curves, one for the industrialized regions (IND) and a second curve for the developing regions (DEV). Hence, we assume that the technology policy will be introduced first in the industrialized regions. In these regions, the share of carbon capture technologies in total installed capacity of fossil power plants is forced to increase gradually from less that 1% in 2010 up to virtually 100% by 2070. For the developing regions we assume that the policy is introduced with a delay of about two decades (2030), however, the diffusion process requires comparatively shorter time since the developing world benefits from the experience gained in industrial regions. This implies that the upfront investments for the initially more expensive CCS systems in niche markets will be covered by industrialized countries. Today's developing countries will profit from this "buy-down" of costs and start deploying CCS at a later stage and lower costs.

The CCS diffusion curves of the policy constraint are shown in Figure 1. Characteristic for the speed of the diffusion process is the time (Δt), which the technology requires to increase its market share from 10 to 90%. We assumed a Δt of 26 years and 19 years for industrialized and developing regions, respectively. These Δts lie well within the ranges reported in the literature for the diffusion of other successful technologies in the past.[3] Nevertheless, it is important to note that our CCS policy portrays a massive technology push steering the very early penetration and rapid diffusion of CCS, particularly if compared to the deployment of CCS illustrated in most carbon mitigation scenarios focusing on the stabilization of atmospheric carbon concentrations (see e.g., [5, 10]). [[insert Figure 1]]

The technology policy is implemented into the model as a lower bound for the share of CCS in the total fossil power generation capacity taking into account the existing power plant stock as well as new installations (and not on individual technologies). By doing so, we give the model the full flexibility to select power plants and capture systems according to an optimal investment strategy. That is, fossil-fired technologies with CO_2 capture will compete against each other to meet the policy constraint. Thus, the resulting fossil power generation mix and the corresponding amounts of carbon sequestered by individual carbon capture technologies depends on a combination of different factors: (1) the development of fossil fuel prices, (2) the cost, performance and learning characteristics of the various power plants, (3) the learning characteristics of the capture technologies, (4) the capture efficiencies and (5) the energy penalties of the associated carbon capture technologies.

Assumptions on capture, transport and storage of CO_2

CCS technologies are represented in the MESSGAE model by so-called "carbon capture clusters". The idea of technology clusters has been applied in several modeling approaches [11, 12]. A technology cluster is defined as a group of technologies sharing a common component (i.e., a common technology or technique). Hence, technology clusters are characterized and defined by related technologies, which interact and cross-enhance each other, contributing to their mutual development [13]. In addition, and as part of the clustering process, spillovers of learning between technologies occur.

The application of the cluster concept to carbon capture technologies is important, because the same capture technique can be used for different types of power plants, leading to significant technological spillover for carbon capture. For example, experience gained through the chemical absorption of CO_2 in PFBC power plants will

[3] See e.g. [9], which includes a comprehensive analysis of Δts for a variety of different technologies. The highest frequency was found for a Δt range of 15-30 years.

increase the knowledge stock and hence also the know-how for building this type of capture technology in any other (non-PFBC) plant. Hence, in the model we separate the capture technologies from the power plants, and group the capture technologies according to the similarity of the capture process into three different clusters (see Table 1). The advantage of this approach is that it permits to endogenize technological learning *and* its spillover for capture technologies independently from the development of the fossil reference plants (i.e., we can distinguish between (1) the learning in the power plants, (2) the learning of the capture technologies, and (3) the learning due to the spillover within a specific cluster of capture technologies.

Table 1 presents the CCS clusters considered for this analysis together with the power plants associated with them. The first two are post-combustion systems, one capture technology encompassing various types of conventional single steam cycle coal plants (CCS_coal) and a second one for conventional single steam cycle gas and NGCC plants (CCS_gas). The third one is a pre-combustion system, which is assumed to be common to IGCC power plants and, as a simplification, to high-temperature fuel cells (CCS_IGFC).

Our assumptions on the present costs of these carbon capture technologies are based on [14], who conducted a comparative cost analysis of carbon capture in conventional (subcritical) and advanced (supercritical) coal power plants, IGCC, and gas combined-cycle power plants. We consider flue gas capture using a monoethanolamine (MEA) solvent for pulverized coal power plants and natural gas combined-cycle turbines, and the shift gas process combined with a physical absorption process (e.g., Selexol) for the IGCC plants. The main cost and performance assumptions are summarized in Table 1. [[insert Table 1]]

The cost for CO_2 transportation and storage are based on estimates from [15], who report a range for the costs of storing CO_2 in deep saline aquifers or depleted oil/gas fields between 3.7 to 11 U$/tC. Here we have adopted the mean value of this range, which corresponds to 7.3 U$/tC. For transportation of captured CO_2 from the sources to the reservoirs, again [15] mention a likely range of 3.7 to 11 U$/tC/100km. For our scenario, we used the mean value and a pipeline length of 250 km, assuming that CO_2 is transported in liquid state, which corresponds to 18.3 US$/tC/250km.

The investment costs of carbon capture technologies (as well as the power plants) are assumed to follow learning curves. The concept of technology learning describes the relationship between the improvement of costs and performance of technologies due to accumulation of experience and knowledge [16]. We use a simplified endogenous formulation, where specific investment costs of technologies improve in tandem with the expansion of total cumulative installed capacity.[4] For the learning rate of CCS technologies we rely on estimates from [17], and adopt a learning rate of 12% for all CCS technologies. The assumptions on the learning rates and investment costs of the power plants are summarized in Table 2. [[insert Table 2]]

Endogenizing learning in to the model allows considering the "up-front" investments that are necessary for a technology to make progress along its learning curve. Typically, when learning curves are endogenized in optimization models with perfect foresight, such as MESSAGE, it results cost-effective for the model to make higher early investments in initially expensive technologies if they exhibit sufficient cost reduction potential in the long term. This highlights the fact that, from a long-term perspective, it could be sensible to invest today on the "buy-down" process of promising technologies that could become competitive in the long run.

[4] The learning concept can be used with a variety of different indicators of technological performance and experience. Here, we focus on specific investment costs as the performance indicator and total cumulative installed capacity as the experience indicator. The specific investment costs of a learning technology are defined as: $SC = a * CC^{-b}$
where:
SC: Specific investment costs (e.g. US$/kW)
CC: Cumulative installed capacity (e.g. gigawatts)
b: Learning elasticity (a constant)
a: Specific cost at unit cumulative capacity
Usually, instead of the learning elasticity b, the learning rate (LR), i.e. the rate at which the cost declines each time the cumulative production doubles, is specified as: $LR = 1 - 2^{-b}$. A learning rate of 20%, for instance means that the specific capital cost of newly installed capacity decreases by 20% for each doubling of total installed capacity. Endogenous learning was added to the MESSAGE model by applying mixed integer programming with a step-wise linearization of the above mentioned formulation (for details see [18]).

A2-CCS: A scenario with clean fossil power

This section summarizes selected scenario results with primary focus on the global level. We describe mainly the A2-CCS scenario, where the policy is applied. For reference purposes a comparison with the case without policy, the A2 scenario, is also given.

Electricity generation

Figure 2 presents a comparison of the global fossil electricity generation mix in the A2 and A2-CCS scenarios for the years 2020, 2050 and 2100. We shall first describe the development of the fossil power generation mix in the baseline (A2), and then proceed to the impacts of the CCS policy. [[insert Figure 2]]

The A2 scenario is characterized by rapid growth of fossil-fired power generation, dominated by coal benefiting from the relatively stable long-term coal price (see Table 2).[5] An important feature of the scenario is that the design of these coal power plants changes substantially due to the compounded effect of technological learning. Existing conventional coal systems (subcritical/PFBC) are gradually phased out. These technologies are substituted by more advanced alternatives with promising learning potential, such as IGCC and high-temperature fuel cells.[6] In the medium term (2050) IGCC is taking over, and the long term (2100) the next generation of coal gasification technologies with high-temperature fuel cells start to dominate fossil electricity generation.

Once the CCS policy is introduced, several changes can be observed. First, due to the introduction of carbon capture, fossil-fired electricity generation becomes more expensive (see Table 2). Hence, fossil power systems decrease their contribution to the global generation mix (by about 30% in 2050 and 2100 respectively). As a consequence, other non-fossil technologies, particularly biomass-based gasification plants and solar power plants, gain additional market shares in A2-CCS (compared to A2).

Secondly, the implementation of the CCS policy leads also to some distinct differences for the evolution of the scenario's power generation mix (Figure 2). Particularly IGCC plants play a dominant role with the CCS policy in place, since they permit the comparatively efficient and less expensive pre-combustion capture of CO_2. In addition, fuel switching takes place towards less carbon-intensive fossil fuels (i.e., NGCC plants), which also allow a competitive combination of electricity production and carbon capture. Advanced coal gasification technologies with high-temperature fuel cells still play a role in the long term, however, their diffusion is restrained due to the CCS policy mainly due to the smaller size of the fossil electricity market, which makes the penetration of comparatively expensive and more advanced technologies increasingly difficult. To some extent the restraint penetration of coal-based high-temperature fuel cells is also due to the comparatively higher operation and maintenance costs (Table 1) as well as the higher CO_2 transportation costs per unit of electricity (compared to natural gas CCS systems).

In our scenario IGCC and NGCC are seen as key complementary building blocks of a strategy for achieving a global fossil electricity system with low carbon emissions. NGCC turbines are, already today, one of the most competitive electricity generation technologies. In contrast, IGCC systems are at a much earlier stage in their life cycle. Nonetheless, they have a promising potential for electricity generation because they offer high fuel flexibility and potential synergies with other processes. Being based on a gasification process that produces a hydrogen-rich synthesis gas out of coal, biomass or other fuels, they enable the joint production of hydrogen (or other fuels or chemicals) together with electricity in so-called poly-generation schemes (see e.g., [19, 20]).

CO_2 emissions reductions due to the CCS policy

Figure 3a depicts the amounts of captured CO_2 along the time horizon in the A2-CCS scenario. Due to the introduction of the CCS policy, the amounts of captured carbon increase gradually over time. The cumulative storage needs of the CCS policy over the course of the century are about 380 GtC, which is well below recent estimates for the storage potential of geological formations given in a number of studies [15, 21, 22].

[5] Note that the share of non-fossil electricity generation is increasing over time in both scenarios (see Table 2).

[6] Learning rates for alternative fossil technologies as well as the resulting investment costs due to technological learning are presented in Table 2.

The largest amount of carbon is captured by the CCS_IGFC technology (mainly from IGCC power plants). Smaller but still significant amounts are captured by the CCS_gas technology (from gas-fired NGCC turbines). As conventional coal-fired power plants are displaced from the global generation mix, the capture technology associated to them (CCS_coal) plays only a minimal transition role. In the long term, pre-combustion systems in IGCC plants, with comparatively low "add-on" costs and energy penalties (compared to post-combustion capture systems) dominate the carbon capture mix.

The development of the global energy-related CO_2 emissions in the A2-CCS and the A2 scenario are shown in Figure 3b. In the A2 scenario the carbon emissions from the global energy system follow a fast growth path reaching around 29 GtC in 2100. This represents more than a four-fold increase as compared to the emissions in the year 2000. [[insert Figure 3]]

With the CCS policy in place, the growth in emissions is slowed down significantly, and global carbon emissions are reduced in the long term by about 20% (in 2100). Nevertheless, the cutbacks in emissions due to CCS in the power sector are largely compensated by the increasing demand for fossil fuels in other sectors such as transportation, leading in the A2-CCS scenario on aggregate still to an increase in emissions by a factor of more than three until 2100 (Figure 3b).[7] We find that strategies with focus on the electricity sector only – as our CCS policy - will not be sufficient to stabilize global carbon emissions. This has important implications for policy making, highlighting the need for integrated policies that include a portfolio of mitigation measures across all energy, industry, and agricultural sectors [23].

Financing a CCS-based electricity system

The costs of financing the CCS policy are presented in Table 3. As costs for the CCS policy we consider (1) investment costs and (2) variable and fixed operation and maintenance costs of the CCS systems including capture (separation plus compression), transport, and storage. The upfront investments required to raise the share of CCS in the industrialized world to about 3.5% (Figure 1) is seen to be about 70 billion US$ over the next 20 years. This corresponds to about 67 GW of CCS installations by 2020. Clearly, the costs of implementing the policy increase over time as the CCS policy becomes more stringent (Figure 1). We estimate global cumulative costs of more than 2.5 trillion US$ up to 2050 and about 20 trillion US$ over the course of the century. This corresponds to a share of about 0.2% of the total global energy systems costs in the initial phase of the market introduction (up to 2020), rising over time to about 4% in the second half of the century.

The costs of the CCS policy are found to be relatively modest, particularly if compared to the total energy systems costs. Nevertheless, it should be emphasized that the financial requirements of making such a policy operational are not minimal when put side by side with other salient investment needs. E.g., connecting the poor to the electricity grid, providing every individual in the world with electricity in 2020 would require 30 billion US$ a year between 2000 and 2020 [24]. The annual costs of the CCS policy up to 2020 correspond to roughly 10% of this sum. [[insert Table 3]]

Summary and conclusions

This paper has analyzed the implications of a technology policy for carbon capture and storage technologies in a long-term scenario of the global energy system. With the imposition of the CCS policy on the global electricity system, significant changes take place in the fossil-fired share of the generation mix. Technologies are chosen, which provide the most cost-effective combination between electricity generation and carbon capture. Specifically, coal-fired integrated gasification combined-cycle (IGCC) plants appear as the most attractive option in the long run. Besides them, natural gas combined cycle (NGCC) turbines also play an important role.

[7] Note that in addition to the above-mentioned increase in demand, also the implementation of the CCS policy itself leads to some increase of CO_2 emissions in the non-electric sectors. This is primarily due to the elevated price of electricity due to CCS, which drives the substitution of electricity by other carbon-intensive energy carriers (partly coal-based methanol and H_2, and to some extend direct use of fossil fuels). The net effect of these substitution processes is leakage of CO_2 from the electric to non-electric sectors, making the CCS policy less effective. Compare e.g. 8.5 GtC of carbon capture and storage from power plants to 5.3 GtC of net emissions reductions in 2100 in the A2-CCS scenario (Figure 3).

The switch to a long-term fully integrated CCS-based electricity system is seen to be feasible at relatively modest costs. The initial costs of the CCS policy for the creation of niche markets in the industrialized countries are found to be 70 billion US$ over the next 20 years. The costs for the widespread diffusion of CCS over the course of the century is estimated to be about 20 trillion US$, corresponding to about 4% of total global energy-related expenditures during this period.

Our analysis shows also that even a very early and rapid diffusion of CCS technologies in the power sector will not be sufficient for the stabilization of global carbon emissions. Achieving this goal would require accompanying measures covering all GHG-intensive economic sectors with particular focus on the decarbonization of the transportation.

Finally, we want to highlight that although CCS has large economic potential as illustrated in this paper, a number of issues related to the storage of CO_2 are poorly understood and need further research. First, a better assessment of the storage potential of different reservoirs, their leakage characteristics and associated risks and costs is required. In addition, the environmental impacts of storage and leakage need to be quantified and the overall effectiveness of the storage schemes has to be evaluated. Instrumental in this process will be the development of measurement, monitoring and verification technologies/schemes, which could offer a sound quantitative basis for a comprehensive risk assessment of CO_2 storage, and hence, raise scientific and public confidence in this option.

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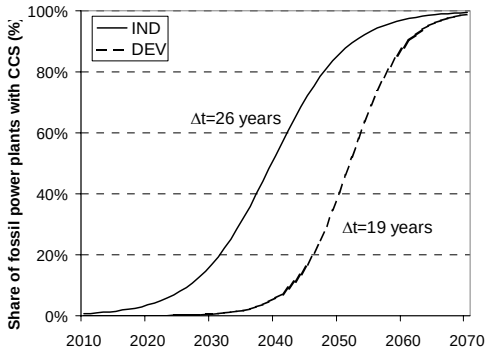

Figure 1: Logistic penetration curves assumed for the diffusion carbon capture technologies in the A2-CCS scenario for the industrialized (IND) and developing regions (DEV). Δt is the time, which carbon capture technologies require to increase their market share from 10 to 90%.

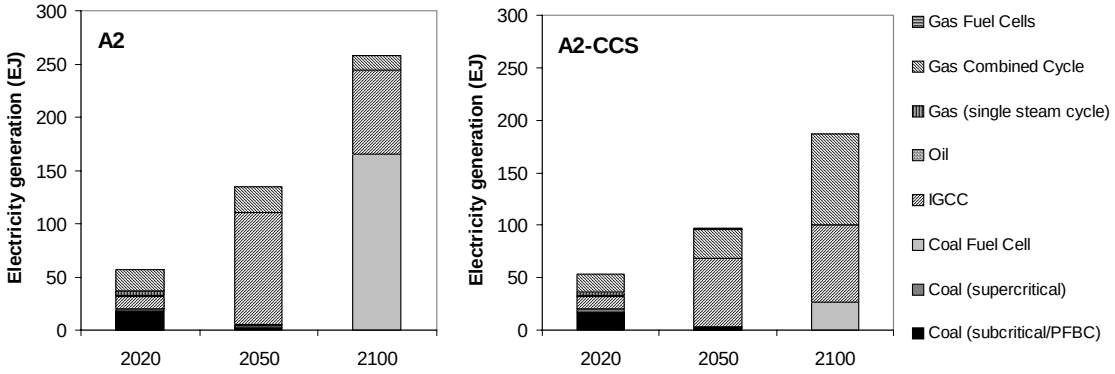

Figure 2: Contribution of fossil power plants to the global electricity generation in the A2 and the A2-CCS scenario.

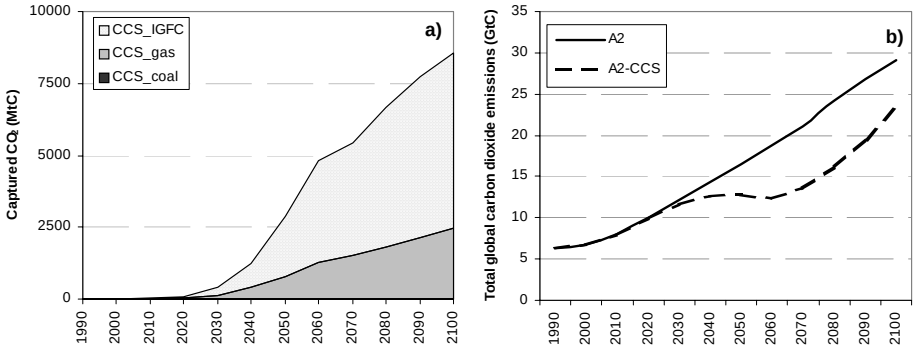

Figure 3: a) Captured CO_2 in the A2-CCS scenario for the period 1990 to 2100. The contributions of the three CCS clusters in MtC are distinguished (left hand side). b) Development of the global energy-related carbon dioxide emissions (GtC) in the A2 and A2-CCS scenarios for the period 1990 to 2100 (right hand side).

Table 1: Main characteristics of carbon capture technologies in this analysis.

	Investment costs (US$/kW)	O&M costs (cents/kWh)	Energy penalty (%)	Efficiency of carbon capture (%)
CCS_coal	940	0.85	25	90
CCS_gas	578	0.26	13	90
CCS_IGFC	509	0.37	15	90

Table 2: Selected scenario indicators: (1) exogenous drivers (POP, GDP), (2) learning rates and imputed investment costs due to endogenous technological learning, (3) fuel costs, (4) electricity prices, and (5) power generation in the A2 and A2-CCS scenarios for the years 2000, 2050, and 2100 respectively.

	Learning rate	2000	2050		2100	
			A2	A2-CCS	A2	A2-CCS
Exogenous drivers (world):						
GDP (mer, trillion 1990$)	n.a.	25	81.6	81.6	242.8	242.8
Population (billion)	n.a.	6.2	11.3	11.3	15.1	15.1
Reference power plants (investment costs in $/kW):						
Subcritical coal (coal conv.)	0%	1000-1300	1000-1300	1000-1300	1000-1300	1000-1300
Supercritical coal (coal adv.)	3%	1165	1165	1165	1165	1165
NGCC	7%	542	420	420	420	360
Single steam cycle gas PPL (gas conv.)	0%	710	710	710	710	710
IGCC	10%	1400	770	770	630	630
High temperature fuel cell (coal)	10%	2000	1550	2000	890	1100
High temperature fuel cell (gas)	10%	1150	1150	900	1150	900
Carbon capture clusters (investment costs in $/kW):						
CCT_coal	12%	940	-	940	-	940
CCT_gas	12%	578	-	488	-	260
CCT_IGFC	12%	509	-	430	-	230
Average fuel costs / electricity prices						
Natural gas ($/GJ)	n.a.	3.3	5.6	6.1	9.5	9.9
Coal ($/GJ)	n.a.	1.2	1.6	1.6	2.6	2.7
Electricity (cents/kWh)	n.a.	3.2	4.4	5.7	7.5	10.8
Global fossil power generation (EJ):	n.a.	33	135	97	258	187
Global fossil power generation including CCS (EJ):	n.a.	-	-	60	-	187
Share of fossil power in total electricity (%):	n.a.	62%	61%	47%	48%	36%

Table 3: Costs of carbon capture, transportation and storage compared to total global energy systems costs in the A2-CCS scenario.

	Cumulative costs (trillion US$)			Share of CCS in total energy systems costs (%)
	CO_2 capture systems	CO_2 transportation and sequestration	Total energy systems costs	
2000-2020	0.05	0.02	34	0.2%
2020-2050	1.7	0.8	114	2.2%

2050-2100	10.7	7.8	504	3.7%

Costs include investment costs and variable and fixed operation and maintenance costs of the energy infrastructure. Transaction costs of e.g., measurement, monitoring and verification of transport and storage of CO_2 or additional requirements for operation and maintenance of the storage sites (e.g., for leakage repair) are subject to large uncertainties and are not taken into account here.