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J. Gale
IEA Greenhouse Gas R&D Programme,
Cheltenham, Gloucestershire, UK

Y. Kaya
RITE, Kyoto, Japan

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PROSPECTS FOR CARBON CAPTURE AND SEQUESTRATION TECHNOLOGIES ASSUMING THEIR TECHNOLOGICAL LEARNING**

Keywan Riahi[1,*], Edward S. Rubin[2], Leo Schrattenholzer[1]

[1] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria
[2] Carnegie Mellon University, Baker Hall 128A, 5000 Forbes Avenue, Pittsburgh, PA 15213, U.S.A

ABSTRACT

This paper analyzes potentials of carbon capture and sequestration technologies (CCT) in a set of long-term energy-economic-environmental scenarios based on alternative assumptions for technological progress of CCT. In order to get a reasonable guide to future technological progress in managing CO_2 emissions, we review past experience in controlling sulfur dioxide emissions (SO_2) from power plants. By doing so, we quantify a "learning curve" for CCT, which describes the relationship between the improvement of costs due to accumulation of experience in CCT construction. We incorporate the learning curve into the energy modeling framework MESSAGE-MACRO and develop greenhouse gas emissions scenarios of economic, demographic, and energy demand development, where alternative policy cases lead to the stabilization of atmospheric CO_2 concentrations at 550 parts per million by volume (ppmv) by the end of the 21st century. Due to the assumed technological learning, costs of the emissions reduction for CCT drop rapidly and in parallel with the massive introduction of CCT on the global scale. Compared to scenarios based on static cost assumptions for CCT, the contribution of carbon sequestration is about 50 percent higher in the case of learning resulting in cumulative sequestration of CO_2 ranging from 150 to 250 billion (10^9) tons carbon during the 21st century. The results illustrate that assumptions on technological change are a critical determinant of future characteristics of the energy system, hence indicating the importance of long-term technology policies in reducing greenhouse gas emissions and climate change.

INTRODUCTION

The mitigation of adverse environmental impacts due to climate change requires the reduction of carbon dioxide emissions from the energy sector, the dominant source of global greenhouse-gas emissions. There are a variety of possibilities to reduce carbon emissions, ranging from the enhancement of energy efficiency to the replacement of fossil-based energy production by zero-carbon technologies. Most of the currently available mitigation technologies, however, are more costly and technologically inferior in some ways compared to the older and more "mature" fossil alternatives. Thus, there is an increasing interest among experts and policy makers in "add-on" environmental strategies to combine state-of-the-art fossil technologies with advanced technologies that capture carbon for subsequent sequestration. Such strategies, if successfully implemented, could enable the continuous use of fossil energy carries at low (or almost zero) emissions. Present costs for carbon capture technologies (CCT) to reduce emissions are between 35 and 264 $/tC (DOE, 1999), corresponding to a prohibitive cost increase for electricity of at least 25 $/MWh. Given the current costs, it is unlikely that CCT successfully enter the energy market, even if international

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* Corresponding author: Keywan Riahi is a Research Scholar at the International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria, Tel: +43-2236-807-491, Fax: +43-2236-807-488, Email: riahi@iiasa.ac.at.

agreements and efficient institutions for CO_2 abatement would exist. Their pervasive diffusion will require substantial efforts to induce "technological learning", which could accomplish considerable cost reductions in the long run. Thus, in this paper we quantify the potential and achievable pace of technological learning for CCTs. We incorporate the learning into the energy modeling framework MESSAGE-MACRO (Messner and Schrattenholzer, 2000) and develop a set of global greenhouse gas emissions scenarios. Within this frame, we analyze the potential of CCTs in the context of other main mitigation options, such as fuel switching and enhanced energy conservation.

ESTIMATION OF LEARNING CURVES FOR CARBON CAPTURE TECHNOLOGIES

Generally, costs – and other indicators of technology performance – improve as experience is gained by producers (learning-by-doing) and consumers (learning-by-using). In order to get a reasonable guide to future technological progress of carbon capture technologies, past experience in controlling sulfur dioxide emissions (SO_2) from power plants was reviewed (Taylor 2001). In particular, we have estimated learning rates of capital and operating cost reduction for the most common flue gas desulfurization (FGD) technology used at coal-fired power plants for SO_2 capture. This technology (commonly known as SO_2 "scrubbers") employs similar principles of operation as currently commercial CO_2 capture systems that use chemical sorbents to remove CO_2 from gas mixtures such as combustion products. For FGD systems, investment costs declined by 13% for each doubling of capacity worldwide, and this is therefore also the value we used to quantify the "learning curve" for CCTs.[1]

SCENARIO DEVELOPMENT

In order to obtain a plausible range of estimates for the deployment of CCT, we analyze two alternative baseline scenarios, depicting future worlds of increasing carbon emissions with presumably high impacts due to climate change. For each we develop two carbon mitigation scenarios (one with and one without CCT learning) aiming at the stabilization of atmospheric carbon concentrations at about 550 ppmv. The sequel of this section first presents the main characteristics of the respective baseline and carbon mitigation scenarios, proceeding later to the implications for CCT.

Baseline reference scenarios:

Both baseline scenarios are selected from the set of 40 IPCC-SRES reference scenarios (IPCC-SRES, 2000). The B2-MESSAGE scenario (Riahi and Roehrl, 2000a) was selected because it is a kind of "middle of the road" (dynamics-as-usual) scenario. In addition, we selected the A2-MESSAGE scenario (Riahi and Roehrl, 2000b), since A2 portrays a fossil-intensive future characterized by heavy reliance on coal-based energy production. A2 and B2 are based on different assumptions of socioeconomic development, technological progress, and political change. They result in widely differing world energy systems, which are cost-optimal strategies under the given assumptions, and lead to a wide range of emissions levels (**Figure 1**). Assumptions for the main scenario drivers and results are presented in TABLE 1.

Carbon mitigation scenarios:

Two stabilization scenarios for each baseline were developed - one assuming constant costs for CCTs (A2-550s, B2-550s), and one including learning for CCTs (A2-550t, B2-550t). The resulting CO_2 emissions trajectories of the mitigation scenarios are shown in **Figure 1**. They are characterized by a peak of about 9 to 12 GtC around the middle of the 21st century. Subsequently, emissions decline to slightly less than the 1990 emissions level (6 GtC) by 2100. The emissions in the baseline and the stabilization scenarios is quite similar through 2020, and only after 2020 do emissions reductions become pronounced. This is partly because power plants have lifetimes on the order of 30-40 years, which makes for slow turnover in the energy capital stock, and partly because of the temporal flexibility built into the concentration constraint.

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[1] The "learning curve" equation is found to describe the decline in production costs for a wide range of manufacturing activities remarkably well (e.g., Dutton and Thomas, 1984; Nakićenović et al., 1998; McDonald and Schrattenholzer, 2001). The relationship is given by an equation of the form: cost = a* (cumulative number of units produced) $^{-b}$, where –b gives the slope for the improvement in costs (hours) in producing the units. On a log-log scale this equation plots as a straight line with slope -b. Generally, the "progress ratio" (2^{-b}) describes the ratio of current cost to initial cost after a doubling of production. Thus, a progress ratio of 0.80 meant that costs decreased by 20 percent for each doubling. Some authors therefore prefer the term "learning rate" for the latter quantity.

The model is free to choose when and where to reduce carbon emissions, and later reductions coinciding with turnover in capital plant are usually cheaper, because of both technological progress and discounting[2].

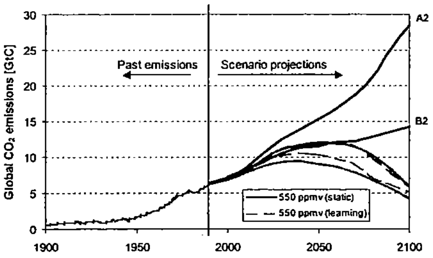

Figure 1: Global carbon dioxide emissions in the A2 and B2 baseline scenarios, and in the respective stabilization scenarios with and without learning for CCT.

TABLE 1

OVERVIEW OF SCENARIO DRIVERS AND RESULTS

COMPARE WITH 1990 VALUES FOR POPULATION (5.3 BILLION), GDP (20.9 TRILLION (1990)US$), PRIMARY ENERGY (352 EJ), TOTAL CO_2 EMISSIONS (6.2 GTC), CO_2 CONCENTRATION (354 PPMV).

	Year	Baseline scenarios		Stabilization scenarios			
				Static CCTs		Learning CCTs	
Scenario		A2	B2	A2-550s	B2-550s	A2-550t	B2-550t
Population (billion)	2050	*11.3*	*9.4*	*11.3*	*9.4*	*11.3*	*9.4*
	2100	*15.1*	*10.4*	*15.1*	*10.4*	*15.1*	*10.4*
Global gross domestic product (trillion 1990US$)	2050	*82*	*110*	*81*	*109*	*81*	*109*
	2100	*243*	*235*	*236*	*231*	*237*	*231*
Primary energy (EJ)	2050	*1014*	*869*	*959*	*881*	*960*	*883*
	2100	*1921*	*1357*	*1571*	*1227*	*1636*	*1257*
Cumulative carbon emissions (GtC)	1990-2100	*1527*	*1212*	*992*	*948*	*990*	*950*
Cumulative carbon sequestration (GtC)	1990-2100	-	-	*167*	*90*	*243*	*137*
Carbon concentrations (ppmv)	2100	*783*	*603*	*550*	*550*	*550*	*550*

Although the resulting emissions trajectories of the four stabilization scenarios are similar, we shall show below that the contributions of individual mitigation measures to bring down emissions differ significantly.

THREE KINDS OF MITIGATION MEASURES

Applying the carbon concentration constraint to the baseline scenarios results in significant changes of energy demand and technology mix. Compared to the respective baseline scenarios, three principal contributors were identified by MESSAGE and MACRO as the most cost-effective route to meet the required stabilization target:

- Fuel switching away from carbon-intensive fuels such as coal.
- Scrubbing and removing CO_2 in power plants and during the production of synthetic fuels, mainly methanol and hydrogen.
- Lower energy demand (enhanced energy conservation) of the stabilization case compared to the baseline counterpart, due to higher energy costs in the stabilization cases compared to their baseline scenario counterparts.

The carbon reductions of each of the mitigation measures in the stabilization scenarios are summarized in TABLE 2. In all stabilization scenarios the largest reductions comes from structural changes in the energy system. To satisfy the carbon constraint, all mitigation scenarios make pronounced shifts to less carbon-intensive primary-energy resources, and coal's share of primary energy decreases considerably. The second most important contribution is due to carbon capture and sequestration, where the emissions reductions are

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[2] For the scenarios presented in this paper, a discount rate of 5% was applied.

particularly high in the case of learning CCT technologies. Cost improvements in the case of technological learning for CCT result in additional markets for carbon capture and enable comparatively higher shares of fossil energy production, compared to the cases with constant CCT costs (TABLE 2). As illustrated by the results, each of the three main mitigation measures is important, and none of the suggested mitigation options alone is sufficient to meet a 550 ppmv stabilization target. Hence, we conclude that effective mitigation strategies have to take into account the whole portfolio of technological possibilities, which includes also carbon capture with subsequent sequestration.

TABLE 2

EMISSIONS REDUCTIONS (IN GTC) OF THE MAIN MITIGATION MEASURES IN THE STABILIZATION SCENARIOS FOR THE YEARS 2050 AND 2100.

	Demand reduction		Fuel switching		CO_2 capture and sequestration		Total	
	2050	2100	2050	2100	2050	2100	2050	2100
Static CCTs								
A2-550s	*0.3*	*3.6*	*2.2*	*12.5*	*0.5*	*5.8*	*3.0*	*21.9*
B2-550s	*0.3*	*1.3*	*1.4*	*3.9*	*0.3*	*3.0*	*2.0*	*8.2*
Learning CCTs								
A2-550t	*0.3*	*3.7*	*2.1*	*9.5*	*0.4*	*8.9*	*2.9*	*22.0*
B2-550t	*0.3*	*1.5*	*1.1*	*4.0*	*0.3*	*4.0*	*1.7*	*9.5*

COSTS OF CARBON CAPTURE AND SEQUESTRATION

The capturing of CO_2 accounts for about three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system. The cost assumptions in the scenarios are based upon estimates from several recent studies (Rubin, et al., 2001; EPRI & USDOE, 2000; Simbeck,1999; Herzog,1999) assuming that CO_2 is captured from flue gases by currently available chemical absorption systems. Generally, the capturing of CO_2 is associated with efficiency losses of the power generation process, and additional costs for the carbon capture facilities. The (aggregated) carbon abatement costs for coal technologies resulting from our assumptions are 196 US$/tC, compared to 137 US$/tC for natural-gas (both figures including transportation and disposal).[3] In the stabilization scenarios with constant costs (A2-550s, B2-550s), we assumed that the capital costs for CCTs remain constant over time. In contrast, in the case of learning CCTs (A2-550t, B2-550t), we assumed that their costs decrease with accumulated experience in CCT construction. The development of carbon reduction costs as a function of cumulative installed CCT capacities in the scenarios is illustrated in **Figure 2a**. Due to technological learning, CCT costs drop rapidly in the stabilization scenarios, leading to cost reductions by a factor of four until the end of the century. In line with the development of costs, CCT technologies diffuse pervasively into the energy markets, accomplishing the continuous use of fossil fuels at relatively modest costs and low carbon emissions. Total reduction costs for natural gas technologies drop to 34-38 US$/tC, and those of coal technologies to 41-61 US$/tC (**Figure 2a**).[4]

CCT MARKET SHARES IN THE ELECTRICITY SECTOR

The scenario's market shares of CCT technologies are the result of complex interactions between demand-pull to supply-push activities. On the demand side, the carbon concentration limit enforces the introduction of new and advanced technologies with low carbon intensities. On the supply side, increasing returns from induced technological learning of CCTs, pushes their market penetration (in the t-scenarios) from the supply side. Together, this results in very successful penetration of CCT technologies in the scenarios with technological learning, compared to scenarios with static cost assumptions (**Figure 2b**). Initially, CCTs are expensive and limited in their application. They have to first prove themselves during the demonstration phase where performance rather than costs is the overriding criterion. Then subsequent improvements and

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[3] Costs of carbon removal in synthetic fuels production (and from IGCC) were assumed to be 46 US$/tC (inclusive transportation and disposal). For transportation and disposal we assumed that captured CO2 is transported in liquid state, through 250 km of pipeline and disposed of in geological formations. The cost for CO2 transportation is based on estimates from the IEA (1999), assuming originally a distance of 500 km at 45 $/tC. Here, half the distance and an economy of scale factor of 2/3, which results in 28 $/tC of transport plus disposal cost is assumed.

[4] The development of the carbon reduction costs for CCTs depend also on the regional resource availability and the development of fuel costs. In addition, assumptions on technological change for the power plants themselves influence the carbon reduction costs of CCTs. A sensitivity analysis using different initial costs for CCTs suggests that the learning rate might be the most decisive factor, not only for the costs, but also for the successful diffusion and dissemination of CCTs (given a specific carbon constraint).

cost reductions lead to a wider application. Finally, growth rates slow down as markets become saturated. The diffusion of CCTs proceeds along a typical S-shaped pattern: slow at the beginning, followed by accelerating growth that ultimately slows down as markets become saturated. Comparing the diffusion of CCTs in scenarios with learning (A2-550t, B2-550t) with those assuming constant costs of these technologies (A2-550s, B2-550s) shows that the market penetration of CCTs is accelerated due to technological learning. Particularly, the carbon capture from coal technologies benefits considerably from the learning effect, leading to global market shares of more than 90 percent in 2100 (compared to 60-70 percent in the case of static costs). At the end of the century, almost all fossil power plants are equipped with carbon capture technologies in the case of learning (**Figure 2**b). The resulting CO_2 emissions from coal and natural gas-based power generation are also shown in **Figure 2**b. The CO_2 emissions path in the scenarios follows an inverse U-shaped pattern similar to environmental Kuznets curves, observed for other pollutant emissions in the past, such as sulfur (Grübler, 1998). After initial growth, CO_2 emissions peak around the middle of the century and decline later, when the carbon capture and sequestration technologies gain considerable market shares. Most notably, until the end of the century, global CO_2 emissions from coal and gas power generation decreases by more than a factor of three, while power generation from these technologies grow three to five times their present production (about 27 EJ).

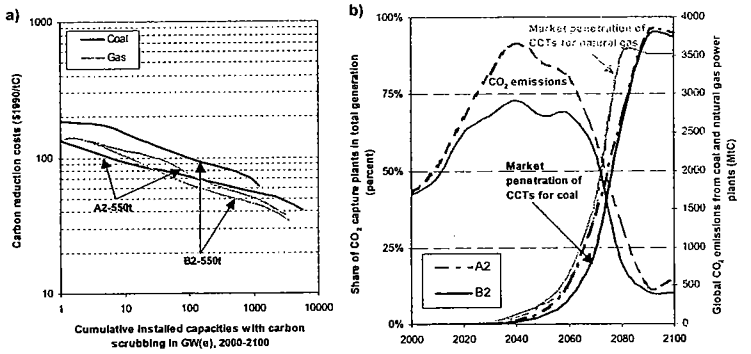

Figure 2: ***(a)*** Technological learning of carbon capture technologies in the A2-550t and B2-550t scenarios, illustrated as decreasing specific carbon reduction costs over accumulated experience (cumulative installed power generation capacities). ***(b)*** Market penetration of "learning" CCT technologies for natural-gas and coal power plants in the A2-550t and B2-550t scenarios (left-hand axis). Dashed lines depict the development in the A2-550t scenario, and uninterrupted lines in B2-550t. Also shown are the aggregated CO_2 emissions from coal and natural-gas power generation in the respective scenarios (right-hand axis).

The cumulative carbon sequestration in the scenarios – from 1990 to the 2100 – are shown above in TABLE 1. Generally, the amounts scrubbed depend strongly on (1) the socio-economic and technological assumptions in the baseline scenarios; and (2) the assumptions with respect to technological learning for CCT technologies. Cumulative carbon sequestration is higher in the case of the A2 scenarios compared to B2, and higher in scenarios with learning CCTs than in those with static cost assumptions.[5] In the case of learning CCT's cumulative carbon emissions from 1990 to 2100 range between 137 and 243 GtC. This corresponds to a 50 percent increase of sequestration due to learning effect for CCTs, compared to the scenarios with static costs (90 to 167 GtC).[6]

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[5] Since the A2 baseline depicts a future of heavy reliance on coal technologies, cumulative carbon sequestration is particularly high in A2, calling for environmentally compatible solutions that permit the continuous use of coal at low carbon emissions. In contrast, fossil-based power generation plays a less prominent role in the B2 baseline scenario, and is mainly dominated by advanced natural gas technologies, in particular gas-combined-cycle. Hence, in A2 coal scrubbers dominate, while in B2 natural-gas scrubbers account for the bulk of the reductions.

[6] The amount of carbon emissions that has been captured in the scenarios is well below the maximum potential of storage capacity of depleted oil and gas fields alone (Herzog 2001, Riahi *et al.*, 2002). Nevertheless, it still has to be proved, whether all reservoirs proposed for carbon sequestration are effective, safe and environmentally sound.

SUMMARY AND CONCLUSIONS

Our analysis shows that the timing, costs, and contribution of carbon mitigation measures strongly depend on (1) the socio-economic and technological assumptions in the baseline scenario, and (2) the assumed learning potential of carbon capture and sequestration technologies. Assuming that CCT technologies learn at a similar pace as SO_2 abatement technologies in the past, the long-term reduction potential for CCT is vast; in our scenarios ranging between 140 and 250 GtC of cumulative CO_2 sequestration (from 1990 to 2100, assuming a stabilization target of 550 ppmv). This is particularly due to large-scale investments into CCT and the accumulation of experience, which leads to rapid cost decreases of these technologies. Even though their widespread deployment requires decades to come, we conclude that carbon capture and sequestration is one of the obvious priority candidates for long-term technology policies and enhanced R&D efforts to hedge against the risk associated with high environmental impacts of climate change. Our scenario analysis also showed that the capturing of carbon with subsequent sequestration might not be sufficient to meet a 550 ppmv stabilization constraint (in the year 2100), even in the case of a very successful market penetration for CCTs. In addition to carbon sequestration, reaching this goal must also include better energy efficiency and the increased use of low-carbon emitting energy sources, in particular fuel switching, primarily away from carbon-intensive coal to low or zero-carbon fuels. Acknowledging the major differences between scenarios with learning CCTs and those with static cost assumptions leads us to two important conclusions. First, improved future models should be capable of characterizing future changes in cost and performance resulting from technology innovation (learning). Second, climate policies need to be extended to include technology policies, in order to make the diffusion of environmentally sound technologies operational in the long run. This calls particularly for early action to accomplish the required cost and performance improvements in the long term, including the creation of niche markets, the development of small-scale demonstration plants, and targeted R&D.

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