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Long-term Perspectives for Carbon Capture in Power Plants: Scenarios for the 21st Century

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Contents

Abstract

The report analyzes the role of fossil-fired power plants equipped with carbon capture systems in long-term scenarios of the global energy system representing technological change as an endogenous process. 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. In particular, we examine the potential costs and the contribution that such a policy could offer in reducing energy-related carbon dioxide emissions and highlight some of the technologies that may play a role in doing so. The analysis is carried out with the global energy-systems optimization MESSAGE model (Messner and Strubegger 1995) considering endogenous technology learning for fossil power plants and the corresponding carbon capture technologies, such that they experience cost reductions as a function of accumulated capacity installations. The report describes two baseline scenarios: (1) including learning for fossil power plants and (2) the other with no learning. In addition, the analysis examines three cases that are based on a technology policy that enforces an increasing share of fossil fuel power plants with carbon capture, distinguishing between future worlds assuming: (1) no learning for fossil systems, (2) learning just for the carbon capture component, and (3) full learning for the reference plants as well as for the carbon capture systems.

The analysis shows that the introduction of a policy for carbon capture and storage would lead to considerable reductions in carbon emissions in the electricity sector and major changes in the power generation mix. Technologies are chosen, that provide the most cost-effective combination between electricity generation and carbon capture, fostering the penetration of advanced fossil technologies. In particular, coal gasification systems such as, IGCC power plants and high temperature fuel cells, and in addition gas-fired combined cycle power plants appear as the most attractive fossil-fired electricity generation options.

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Long-term Perspectives for Carbon Capture in Power Plants: Scenarios for the 21st Century

Keywan Riahi, Leonardo Barreto, Shilpa Rao

1. Introduction

Already since the early 1970s a number of stringent environmental policies on fossil-fired power plants became effective in the mitigation of various pollutant emissions, such as SO_2 or nitrogen oxides. One important not-yet-addressed aspect concerns, however, the carbon emissions from fossil power generation, particularly relevant in relation to possible adverse impacts of climate change (IPCC, 2001).

Hedging against the risks of climate change would require 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 (Riahi and Roehrl, 2000). 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. Hence, fossil power plants are bound to continue playing a significant role in meeting the increasing global electricity demand well into the future. Even under moderate assumptions for the growth of energy demand this would lead to a very significant increase of global carbon emissions (Nakićenović and Riahi, 2001). Technologies are required, which are capable of "bridging" the long-term transformation of today's energy system into a less carbon-intensive one, 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 (e.g., renewables), which if introduced at the same pace as carbon capture, would require fundamental structural changes and the premature replacement of fossil power generation.

The assessment of the potential role of technologies requires an adequate representation of the main mechanisms of technological change, which is one of the principal driving forces in shaping the evolution of energy systems. Its dynamics, pace, and direction, however, is subject to large uncertainties, calling for scenario analysis with integrated assessment models evaluating the possible contribution of specific energy technologies under alternative policy configurations. The competitiveness of technologies in different scenarios depends, among other things, on assumptions regarding their cost evolution, i.e., on their patterns of technological learning, and on how such patterns are represented (endogenous or exogenously). The cost assumptions and their methodological treatment in models are important for all technologies but they can be particularly significant for currently expensive and promising emerging technologies, such as carbon capture and sequestration systems.

Previous work (Rubin *et al.*, 2001, Riahi *et al.*, 2002) has illustrated the effects of changes in the cost assumptions for carbon capture technologies in the outcome of integrated assessment models. In particular, it has been shown that introducing cost trends for these technologies in a consistent way with the technological learning concept and under the assumption that they are able to follow the kind of learning patterns that "add-on" scrubbing technologies for other pollutants have shown in the past, their contribution to a carbon mitigation strategy could increase significantly.

In this report we analyze the role of fossil-fired power plants equipped with carbon capture systems in long-term scenarios of the global energy system representing technological change as an endogenous process. 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. In particular, we examine the potential costs and the contribution that such a policy could offer in reducing energy-related carbon dioxide emissions and highlight some of the technologies that may play a role in doing so. The analysis is carried out with the energy-systems optimization MESSAGE model (Messner and Strubegger 1995) considering endogenous technology learning for fossil power plants and the corresponding carbon capture technologies, such that they experience cost reductions as a function of accumulated capacity installations. The report presents five alternative scenarios: two baseline scenarios, which differ with respect to the learning in fossil power plants – one including learning and the other with no learning. In addition, three policy cases are presented, distinguishing between future worlds assuming (1) no learning for fossil systems, (2) learning just for the carbon capture component, and (3) full learning for the reference plants as well as for the carbon capture systems.

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 technologies. In our scenario analysis, we assume *ex-ante* that these policies are in place leading to the introduction of a technology policy for carbon capture systems in the electricity sector. We do not assume any additional carbon mitigation measures in the other sectors or a 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]

We acknowledge that large-scale carbon capture and sequestration systems still face a number of scientific, technical, and economic problems that have to be addressed before they become a viable option in a global greenhouse gases mitigation strategy. In this sense, our scenarios should be regarded solely as an attempt to address the questions: (1) "what-if" carbon capture and storage technologies would be able to overcome those barriers and be deployed successfully and (2) what could be their potential contribution to achieve a clean, low-carbon global power generation sector?

The scenarios are based upon the A2 scenario developed at IIASA for SRES (2000), which portrays a world with relatively moderate economic growth, where electricity needs increase substantially and fossil-based technologies play a major role. With these characteristics, it provides a good context for the examination of the role of carbon capture technologies in the power generation sector. Our policy scenarios are labeled A2-CCT, where the acronym CCT stands for Carbon Capture Technologies. In the A2-CCT scenarios, following a departure in technology and environmental policies from the original A2 world, the fossil-based power systems face pressure to evolve into cleaner configurations with low release of carbon to the atmosphere in the long term.

The remainder of this paper is organized as follows. Section 2 briefly describes carbon capture technologies in the power sector. It also introduces a storyline that illustrates the main scenario characteristics and describes how a world consistent with fossil power plants incorporating carbon

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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) e.g., Riahi *et al.* 2002.

capture might unfold in the future. Section 3 presents the main model and scenario assumptions, with particular emphasis on the technical and economic characteristics of carbon capture technologies. Section 4 describes the methodology, which was applied for the endogenization of learning curves for carbon capture technologies. Main scenario results for the power sector, CO_2 emissions, and implications for carbon capture technologies are presented in Section 5. Finally, Section 6 presents the conclusions and policy implications from our analysis.

2. Towards Clean Fossil Power Plants

2.1 Carbon capture technologies in power plants

The increasing evidence of anthropogenic interference with the earth's climate system and mounting concerns about possible serious adverse impacts of future global climate change (IPCC, 2001) calls for the investigation of alternatives for energy production, conversion and final use with a low release of greenhouse gases to the atmosphere.

Carbon capture and sequestration technologies could permit the use of carbon-rich primary-energy sources while reducing their net emissions to the atmosphere. There are two basic possibilities for carbon sequestration. The first is preventing that carbon produced by human activities reaches the atmosphere. The second is removing carbon from the atmosphere (Socolow, 1997; DOE, 1999a). We are concerned here only with the first alternative. In such context, carbon removal and sequestration requires the capture, transport and long-term storage of the CO_2 resulting from production of fossil-based or biomass-based energy carriers.

The electricity sector is one of the main sources of carbon emissions, responsible for more than 35% of the total CO_2 emissions worldwide. In comparison to other sectors such as transportation, electricity generation appears attractive for carbon mitigation because of the more reduced number of actors, large facilities and a relatively wide range of technological options. Thus, this sector is likely to become a prime target in any greenhouse gases mitigation strategy. Besides other options such as renewable sources, nuclear power, efficiency improvements and fuel switching, emissions to the atmosphere can be reduced through carbon capture in fossil-fired power plants and subsequent long time storage.

The capture of the CO_2 in fossil-fired power plants can be made either before or after the combustion process.[2] Post-combustion capture refers to the separation of CO_2 from the stream of flue gases resulting from fossil fuel combustion. In the conventional approach, combustion occurs in the presence of air and the resulting concentration of CO_2 in the flue gas stream is very low, making the process of separation very laborious. As an alternative, oxygen-based combustion has been proposed, this leads to a more concentrated stream of CO_2, thus facilitating the capture process. In the latter, however, combustion temperatures may become very high. In order to mitigate this problem, O_2/CO_2 cycles can be used, where CO_2 is recycled and used as a working fluid (IEA/CERT, 2002).

The separation and capture of CO_2 from the mix of combustion by-products is typically made using chemical or physical solvents. Although commercially available, solvents still have to be improved. Current research focuses on the development of solvents with higher CO_2 adsorption capacities and rates and which could reduce the significant energy requirements of the capture

[2] While we do here refer to the combustion process, it would be more correct to talk about the electricity production process in general, since technologies like fuel cells do not rely on combustion but on electrochemical conversion for electricity generation.

process (IEA/CERT, 2002). Efforts are also being devoted to the development of alternative technologies, such as membranes for flue gas separation or adsorption.

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 a gas shifting process from which a synthesis gas (syngas), consisting mainly of hydrogen and carbon monoxide, is obtained. A highly concentrated stream of CO_2 can be separated using chemical or physical adsorption, membranes or pressure swing adsorption. The remaining hydrogen-rich syngas is then used as input to the combustion process (IEA/CERT, 2002).

Since the same process is used for hydrogen production from fossil fuels, the application of pre-combustion carbon capture approaches in power plants could foster also the deployment of so-called poly-generation schemes, which co-produce hydrogen and electricity. This could pave the way for the introduction of hydrogen as an energy carrier in the long run, as a suitable complement to electricity, and for the development and deployment of integrated multi-product energy technologies (DOE, 1999b, Williams *et al*., 2000).

Post-combustion capture can be applied to conventional existing fossil-fired power plants. Pre-combustion capture, however, requires technologies that can work with a hydrogen-rich gas efficiently and cleanly. Thus, the latter needs an adaptation and re-design of current technologies, such as combined-cycle turbines (Audus and Jackson, 2000), or the introduction of advanced technologies, such as integrated gasification combined-cycle (IGCC), high temperature fuel cells[3] or a combination of both.

Very likely, carbon capture technologies would be initially introduced as an “add-on” technology for conventional fossil power technologies, thus favoring the conventional post-combustion approach. Later on, as both the power generation and carbon capture technologies evolve, advanced power plants might have carbon capture as a “built-in” feature. This would contribute to optimize the process from the conception and design stages of the power plant and would open the way for advanced O_2/CO_2 cycles and pre-combustion capture approaches.

2.2 The storyline of a clean fossil-power world

This subsection presents the storyline based on which we have adopted a set of assumptions to quantify the policy scenarios presented in Section 5. The storyline is an account of how a future consistent with carbon capture and sequestration technologies might unfold, and gives a brief characterization of its main driving forces. First, we present a qualitative description of the economic, technical, environmental and social developments in the scenario. Finally, we will focus on the role of clean fossil power technologies with carbon capture and sequestration.

The scenarios developed here build upon the IIASA-SRES-A2 scenario (SRES, 2000) with an updated set of technology characteristics for fossil power plants and carbon capture and sequestration technologies. To distinguish the policy scenarios from the original A2, we have labeled them the A2-CCT scenarios, with the acronym CCT referring to carbon capture technologies. In its context, we explore the contribution of fossil power plants that incorporate carbon capture to the global energy system in the long run.

The A2-CCT scenarios are characterized by relatively slow economic growth and a non-converging world, where regional welfare disparities are very slowly reduced along the 21st century. Economic growth follows an uneven increase across world regions, as differences in productivity, social structures and technological change rates remain significant. As for

[3] For instance, solid-oxide fuel cells (SOFC) or molten-carbonate fuel cells (MCFC). For a description of these technologies see e.g., Srinivasan *et al*. (1999).

demographic trends, following a slow decrease in fertility rates, the global population increases along a high-growth path reaching about 15 billion people at the end of the 21st century.

As a consequence of the consolidation of distinct world-regional economic blocks, the globalization process slows down, and international flows of knowledge, people and technology are reduced. Different regions, thus, evolve along dissimilar technological paths and technology transfer between industrialized and developing countries is less significant.

Still, within the different regional systems, business and governments promote the management of natural capital and markets evolve gradually as to value ecosystem services, following mainly regional environmental concerns. With a drive to increase the productivity of regionally-available natural resources and minimize waste, technologies and production schemes are deployed that, while being cost-effective, allow recycling and/or separating materials and substances that could produce undesired environmental effects (Lovins *et al.*, 1999), which in turn could potentially dislocate economic activities, leading to comparative disadvantages.

Technological change in the energy system is relatively slow and highly dependent on regional resource availability. International trade of energy commodities is not very significant since, due to geopolitical reasons, regions seek to reduce their dependence on others. Thus, while some regions evolve towards high-efficiency post-fossil energy systems, others rely on more resource-intensive fossil-based technologies. Rates of change across different fossil technology clusters are similar, but the cluster of coal-based technologies experience somewhat faster improvements, coal being an indigenous resource abundant enough to fuel economic activity, particularly in developing regions. This is a fossil-intensive world, but one that faces pressure to evolve towards a cleaner form. Therefore, clean fossil technologies, environmentally superior to those of today, emerge in the long term.

Business-government partnerships in energy-related research, development, demonstration and deployment activities (summarized as RD3, following PCAST, 1999) help in sharing the costs and overcoming the risks of developing and introducing new energy technologies appropriate to regional needs and resources. However, given the short-term-profit orientation of industrial partners, government intervention is still necessary in filling gaps in long-term energy RD3 needs.

Without the possibility of significant technology spillovers between world regions, the developing world is forced to devote more resources to local science and technology capacity building, recognized as a strategic factor for survival in this divided world. Also, as economies grow, and with the need to carefully manage the regionally available resources, environmental issues gradually become a more relevant topic in their development agenda.

In the A2-CCT scenarios, electricity needs increase substantially. Such growth provides opportunities for technological learning in electricity-related technologies. It also triggers responses as to minimize environmental impacts from the electricity system. As part of the response to those needs, carbon capture technologies are developed and incorporated into power plants, initially as “add-on” devices and later on as a “built-in” feature. With intensified R&D efforts, effective demonstration projects and sound deployment strategies, substantial but achievable performance improvements and cost reductions occur in power plants with carbon capture and they diffuse widely. Large, centralized power plants are favored since they facilitate the capture of carbon and benefit from corresponding economies of scale.

Simultaneously, scientific advances in the understanding of carbon sequestration processes allow a better assessment of the sequestration potential of different reservoirs, their leakage characteristics and associated risks and costs. Together with the development of measurement, monitoring and verification (MMV) technologies, this allows resolving concerns regarding the physical integrity of the carbon storage reservoirs, the environmental impacts of sequestration and the overall effectiveness of the storage schemes. These actions, combined with adequate communication and information-sharing strategies and the imposition of a regulatory and legal regime suitable for the long-term storage case (Reiner and Herzog, 2003), increase the public acceptability of this option. Eventually, a network of pipelines and maritime fleets for the transportation of CO_2 from carbon sources to storage reservoirs is deployed.

Accompanying changes in the electricity generation technologies a number of technologies emerge to enable the transformation of the electrical grid itself into a more flexible, reliable and stable system for transmitting and delivering power and communication signals. An "intelligent" grid with entirely new capabilities materializes, where multiple generation sources and storage systems interact and around which new business models and services are created, as the advantages of new technologies are recognized and valued in the marketplace. Among others, flexible AC transmission systems (FACTS), advanced (e.g., superconducting) cables, new "back-up" concepts, electricity and hydrogen storage systems and advanced control and communication devices are introduced.

3. Main Scenario Assumptions

As mentioned above, the analysis presented here has been carried out with MESSAGE, an energy systems-engineering optimization model with a detailed representation of energy resources and energy extraction, conversion, transportation and end-use technologies. But, although optimization plays an important technical role in our analysis, we emphasize more the "scenario aspect" of our model runs. This is to say that, with a time horizon of 100 years where huge uncertainties exist, a much more decisive role is played by input assumptions. These assumptions, for example, specify the underlying population and economic trends, the amount of primary-energy resources available, the cost reductions and/or performance improvements of different technologies, etc. They are chosen in a consistent way with the underlying scenario storyline. Here we describe those deemed relevant for this exercise.[4]

In the version of the MESSAGE model used for this analysis, the global energy system is disaggregated into four world macro-regions, as follows:

- The OECD90 region groups the countries belonging to the OECD in 1990.
- The REF region brings together the economies-in-transition in the Former Soviet Union and Eastern Europe.
- The ASIA region represents the developing countries in the Asian continent.
- The ALM region covers the rest of the world, grouping countries in sub-Saharan Africa, Latin America and the Middle East.

The first two regions (OECD90 and REF) grouped together will be referred to as industrialized regions (labeled as IND). The ASIA and ALM regions together comprise the developing regions (labeled as DEV) group.

Five scenarios were developed for the purpose of this study. The scenarios share the same socio-economic and demographic assumptions, but differ with respect to the assumptions for technological learning of fossil power plants and carbon capture technologies. The scenario set comprises two baseline scenarios and three scenarios including the CCT technology policy. In the sequel of the report the following labels for the individual scenarios are used:

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[4] Note that a discount rate of 5% has been applied in all our calculations.

Baseline scenarios:

- A2 (no learning) – baseline including no learning
- A2 (PPL learning) – baseline including learning for power plants

Policy cases enforcing the increasing use of carbon capture technologies:

- A2-CCT (no learning) – policy case including no learning
- A2-CCT (CCT learning) – policy case including learning for carbon capture technologies
- A2-CCT (PPL & CCT learning) – policy case including learning for power plants & carbon capture technologies

3.1 Economic and demographic trends

All scenarios presented in this report share the same economic and demographic assumptions. Economic growth follows dissimilar paths in different world regions. Gross World Product (GWP) grows at an average rate of approximately 2.3% per year, reaching approximately 243 trillion US dollars (in 1990 values at market exchange rates) by the end of the 21st century, representing a 12-fold increase with respect to that of the year 1990. Income per capita rises in both industrialized and developing countries but at a different pace and a slow reduction in income inequities across world regions takes place (SRES, 2000). This is a non-converging world. Essentially, the relative isolation between blocks of regions limits the potential of developing regions to "catch up" with the industrialized regions. By the end of the century, the average income per capita in the developing world reaches US$10,957 or only 24% of that of the industrialized one (US$46,235).

The population trajectory underlying the scenarios corresponds to a high population projection reported by Lutz (1996). Due to the lack of educational measures, slow improvement of social conditions and difficulties in changing the traditional role of women in many societies, less open to the outside world, the population in the developing regions grows at a rapid pace. As a consequence, global population follows a high-growth path during the 21st century reaching about 15 billion people in 2100 (12.8 billion in developing countries and 2.2 billion in industrialized ones).

3.2 Assumptions on resources

Assumptions on the fossil-fuel resource availability are based on the estimates reported by Rogner (1997). The categorization distinguishes between conventional and unconventional reserves and resources and reflects increasing degrees of geological uncertainty and decreasing degrees of economic attractiveness. A relatively large availability of oil and gas is assumed. The oil and natural-gas resource base comprises both conventional resources and potential for their enhanced recovery plus unconventional recoverable resources. Following Rogner's (1997) notation, categories I to VI have been considered for gas and categories I-V for oil. Categories I to III represent conventional reserves and resources. Category IV represents the potential for enhanced recovery of the conventional resources. Category V corresponds to the identified reserves of unconventional recoverable oil and gas. Category VI corresponds to the unconventional gas resource estimates.

Coal resources are also based on Rogner (1997) and are considered globally abundant, although they can be limited in some regions. Following Rogner (1997), categories A to E for both hard coal and brown coal have been considered. Category A represents proved recoverable reserves. Category B represents additional recoverable resources. Category C represents additional identified reserves while Categories D and E group together additional resources.

Equally important as the assumptions on the ultimate resource base is the actual resource use in the scenarios. Table 1 summarizes the global hydrocarbon resource availability and the cumulative fossil fuel use of the baseline and policy scenarios. The cumulative resource consumption results from the interplay between the different driving forces involved in the scenario and represents a more appropriate indicator than the exogenously specified resource base.

Table 1: Categories of conventional and unconventional oil, gas and coal reserves, resources and additional occurrences in Zetajoules, ZJ (10^{21} J). The table shows which of the categories are considered in the A2 and A2-CCT scenarios (shaded cells) and presents resulting cumulative extraction of oil, gas and coal in the A2 and A2-CCT scenarios between the years 2000 and 2100.

	Conventional Reserves and Resources	Unconventional Reserves and Resources			Unconventional and Additional Occurrences		Scenario Result Cum. Extraction 2000-2100	
Category	I, II, III	IV	V	VI	VII-VIII	Total	A2 no learning (learning)	A2-CCT no learning (PPL & CCT learning)
Oil	12.4	5.8	1.9	14.1	59.8	94	18.9 (18.9)	19.0 (18.9)
Gas	16.5	2.3	5.8	10.8	801.6	837.1	24.2 (24.1)	25.5 (25.0)
	Proved Recoverable Reserves	Additional Recoverable Resources	Additional Identified Reserves	Additional Resources				
Category	A	B	C	D	E	Total		
Coal	18.7	12.4	23.3	41.4	165.7	261.5	42.1 (45.0)	41.4 (43.1)

For non-fossil resources, such as uranium and renewable energy, future resource potentials are primarily a function of the assumed rates of technological change, energy prices, and other factors such as safety and risk considerations for nuclear power generation.

3.3 Investment costs for electricity generation technologies

The MESSAGE model provides a detailed technology characterization in the electricity sector. Table 2 presents the scenario's investment costs of fossil power generation technologies for the years 2000 and 2100. In the scenarios that consider endogenous learning, the costs of fossil power plants decrease in line with the deployment of the respective technology and the increase in cumulative installed capacity.[5] The learning rates of the fossil reference power plants are based on estimates from IEA, 2000; Nakićenović *et al*., 1998; and Rabitsch, 2001.[6] As shown in Table 2 the potential for learning is higher for today's advanced and comparatively expensive technologies, such as IGCC and high-temperature fuel cells. In the case of learning, the contribution of these technologies increases significantly leading to considerable changes of the future electricity mix (as compared to the cases without learning). The corresponding "buy-down" of costs is shown in Table 2 (for more details on how technological learning is introduced into the model and on the resulting deployment of the electricity generation technologies in the scenarios see Section 4 and Section 5.2).

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[5] In scenarios with no learning for reference power plants their costs are assumed to stay constant over time.

[6] Due to the limited experience with high-temperature fuel cell systems, there is presently no information on their learning rate available. In addition, uncertainty for the learning rate of the single fuel cell component is vast, ranging between 13 to 30% (Schaeffer, 1998; Whitacker, 1998; Kordesch and Simader, 1996). Since the high-temperature fuel cell systems include a number of components with considerably lower learning potential (than the single fuel cell component), we assume for the scenarios a somewhat lower aggregate learning rate of 10%, i.e., the same rate as for IGCC.

Table 2: Investment costs in \$/kW for the year 2000 and 2100 and the assumed learning rate for fossil electricity generation technologies.

	Learning rate	Initial investment costs (base year) \$/kW	Investment costs in 2100, \$/kW				
			A2 (no learning)	A2 (PPL learning)	A2-CCT (no learning)	A2-CCT (CCT learning)	A2-CCT (PPL & CCT learning)
Reference power plants:							
Subcritical coal (coal conv.)	0%	1000-1300	1000-1300	1000-1300	1000-1300	1000-1300	1000-1300
Supercritical coal (coal adv.)	3%	1165	1165	1165	1165	1165	1165
NGCC	7%	542	542	420	542	542	360
Single steam cycle gas PPL (gas conv.)	0%	710	710	710	710	710	710
IGCC	10%	1400	1400	630	1400	1400	630
High temperature fuel cell (coal)	10%	2000	2000	890	2000	2000	1100
High temperature fuel cell (gas)	10%	1150	1150	1150	1150	1150	1150

All five scenarios presented in this report share the same assumptions for the costs of zero-carbon power generation technologies (nuclear & renewables). The cost improvements of these technologies are given exogenously, since due to computational limitations, just a limited number of technologies can be endogenized in the full-scale MESSAGE model. As shown in Table 3, these technologies are assumed to experience noticeable cost reductions, making them increasingly competitive in the long run. The scenario's cost assumptions for categories of zero-carbon technologies are given in Table 3. Each category may contain one or several types of plants. A more detailed description of the technologies can be found in Appendix 1.

Table 3: Range of investment costs in \$/kW for the main categories of zero-carbon electricity generation technologies for the year 2000 and 2100.

Abbreviation	*Technology description*	*Investment costs for selected years (\$/kW)*	
		2000	*2100*
Biomass	various types of biomass power plants	1567 - 1756	1300 - 1400
Nuclear	various types of nuclear power plants	1900 - 2567	1900 - 2300
Hydro	small to large-scale hydro power plants	1000 - 3000	1000 - 3000
Solar	solar thermal power plants, solar PV power plants, and decentralized PV power generation	2756 - 4756	1600 - 2000
Wind	wind power plant	1344	800

3.4 Assumptions on capture, transport and storage of CO_2

This section presents the assumptions on costs and performance of the carbon capture technologies included in our analysis together with costs of CO_2 transport and long-term storage. For this analysis, the investment costs of these carbon capture technologies are assumed to follow learning curves. The description of the approach for endogenizing the learning curves and the assumptions on the corresponding learning parameters are presented in Section 4 below.

The carbon capture technologies are represented as separate technologies in our model. That is, they are not embedded in the power generation technologies. This approach is different from that used by others (see e.g. David and Herzog, 2000; Simbeck, 2001; among others). The advantage of our approach is that it permits to endogenize technological learning and its spillover for capture technologies independently from the development of the fossil reference plants.

In addition, this study uses the concept of "carbon capture clusters". The idea of technology clusters has been applied in several modeling approaches (Seebregts *et al*., 2000; Gritsevskyi and Nakićenović, 2000). Technology clusters are shaped when related technologies interact and enhance each other, contributing to their mutual development (Nakićenović, 1997). As part of the clustering process, spillovers of learning between technologies can occur.

We follow the so-called key technology approach (Seebregts *et al*., 2000), and consider a carbon capture technology that is shared by different power plants. The power plants are associated to each capture technology on the basis of the similarities of their carbon capture approach. Hence, the "carbon capture clusters" learn with the cumulative capacity added across a group of power plants that share similar characteristics concerning the capture process. In addition, also each individual power plant learns independently, based on its own cumulative capacity installations.

Table 4 presents the CCT clusters considered in the MESSAGE model for this analysis together with the power plants associated with them. The first two are post-combustion systems, one encompassing conventional steam-cycle coal power plants (labeled as CCT_coal) and a second capture technology for conventional gas and natural gas combined-cycle plants (CCT_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 (CCT_IGFC).

Table 4: Carbon capture technologies considered in this analysis and power plants associated to them. For a brief description of the electricity generation technologies considered in the model and the corresponding abbreviations see Appendix 1.

Carbon capture technology	Power generation technologies associated
CCT_coal	Conventional coal (coal_stdu, coal_stda), advanced coal (coal_adv)
CCT_gas	Conventional gas power plants and gas combined-cycle turbines (gas_ppl, gas_cc)
CCT_IGFC	Coal-based IGCC (coal_igcc), coal (coal_htfc) and gas-fired (gas_htfc) high temperature fuel cells

Our assumptions for these carbon capture technologies are based on David and Herzog (2000). They conducted a comparative cost analysis of carbon capture for conventional (subcritical) and advanced (supercritical) coal power plants, IGCC and gas combined-cycle turbines assuming commercially available capture technologies. That is, flue gas capture using a Monoethanolamine (MEA) solvent is considered 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. Under this assumption, they estimated costs and efficiencies for a reference plant with no capture and the same plant with carbon capture both for today's conditions and a possible development in 2010. The figures used here correspond to their today's estimation and are summarized in Table 5.

Table 5: Main economic and technical characteristics of carbon capture technologies in this analysis.

	Investment Costs (US$/kW)	O&M Costs (US$/kWh)	Energy Penalty (%)	Efficiency of Carbon Capture (%)
CCT_coal	940	0.85	25	90
CCT_gas	578	0.26	13	90
CCT_IGFC	509	0.37	15	90

The main economic and technical characteristics of the carbon capture clusters used in this analysis are presented in Table 5. Investment costs for the carbon capture technologies have been considered here as the difference in investment costs between plants with and without CO_2 capture. The same applies for operation and maintenance (O&M) costs. In addition, following David and Herzog (2000), the efficiency of the capture process is assumed to be 90%. As a simplification, both the capture efficiency and the "energy penalty" are considered constant along the time horizon. It must be noticed, however, that, as both fossil electricity generation and carbon capture technologies develop and new approaches for carbon capture are conceived and used, significant "energy penalty" reductions could be expected and the capture efficiency could improve. For this exercise, however, we remain on the conservative side regarding potential improvements of the process. Notice also that we do not consider here novel technologies such as membrane systems (e.g., IEA/CERT, 2002).

When applying the concept of "CCT clusters" some simplifications are required. That is, since we are associating different power plants with a common capture technology, average values for the energy penalty and carbon-capture efficiency have to be used. This is an approximate representation but one that helps in having a better representation of the learning process of the carbon-capture technologies.

It should be noted here that the choice of the clusters of learning technologies might have an influence on the results, i.e., with a different clustering the shares of the learning technologies in the model outcome could be different. In addition, in considering clusters where the cumulative capacities of the member technologies are added up to compute the cumulative capacity of the key technology and, therefore, the corresponding cost reduction, we are relying on the assumption that spillovers of learning are full across technologies. That is, we assume that a given technology fully profits from the experience accumulated in other technologies within the same cluster.

The incorporation of carbon capture technologies in the power plants affects their technical and economic characteristics. Table 6 presents the main characteristics of the fossil-fired power plants with carbon capture.

Table 6: Characteristics of power plants with carbon capture. Levelized costs figures exclude fuel costs (for the base year 2000).

		Coal Conv.	Coal Adv.	Coal Fuel Cell	Gas CC	Gas Fuel Cell	IGCC
Reference Plant							
Investment	$/kW	1150	1165	2000	542	1150	1400
O&M	¢/kWh	0.74	0.8	1.65	0.25	0.91	0.79
Efficiency	%	41	43	55	55	60	42
Load factor	%	75	75	65	75	65	75
Plant life	Years	30	30	25	30	25	30
Levelized investment costs	¢/kWh	1.1	1.2	2.5	0.5	1.4	1.4
Total levelized costs	¢/kWh	1.9	2.0	4.1	0.8	2.3	2.2
Carbon Emissions	tC/kWyr	1.98	1.89	1.48	0.88	0.80	1.93
Plant with carbon capture							
Investment	$/kW	2090	2105	2509	1120	1659	1909
O&M	¢/kWh	1.59	1.65	2.02	0.51	1.28	1.16
Efficiency	%	31	32	47	48	51	36
Load factor	%	75	75	65	75	65	75
Plant life	Years	30	30	25	30	25	30
Levelized investment costs	¢/kWh	2.1	2.1	3.1	1.1	2.1	1.9
Carbon emissions	tC/kWyr	0.23	0.22	0.17	0.11	0.10	0.23
Total Levelized Cost	¢/kWh	3.7	3.7	5.1	1.6	3.4	3.1
Carbon Reduction Costs	$/tC	89.4	93.3	67.3	94.2	124	45

Reference plants and plants with carbon capture are shown and levelized costs of electricity production (excluding fuel costs) and carbon mitigation costs are included. Carbon mitigation costs are computed with reference to the same plant without carbon capture.

The costs of CO_2 transportation and storage are based on estimates from Freund *et al.* (2002). They report that a plausible range for costs of storage of CO_2 in deep saline aquifers or depleted oil/gas fields is 1-3 US$/ton CO_2 (3.7-11 US$/ton C). Here we have adopted the mean value of this range, which corresponds to 7.3 US$/ton C, for our calculations. It must be recognized, however, that many uncertainties surround these figures. Storage costs will depend on many factors, among others on the geological characteristics of specific reservoirs and the rates of injection.

As for transportation of captured CO_2 from the sources to the reservoirs, again Freund *et al.* (2002) mention a likely range of 1-3 US$/ton CO_2/100 km (3.7-11 US$/ton C/100 km). Using the mean value and a pipeline length of 250 km, we arrive at 5 US$/ton CO_2/250 km (or 18.3 US$/ton C/250 km), the figure used here. It must be noticed that in pipeline transportation significant economies-of-scale can be achieved.

As for CO_2 storage capacities, given the huge uncertainties that exist in the figures, we have not imposed an upper bound for storage capacity in the model. Nonetheless, in order to provide some perspective on the orders of magnitude of sequestered amounts, in Section 5.4 below we compare the cumulative figures resulting in our A2-CCT scenarios with some estimates available in the literature (IEA, 2001). A more precise assessment of the storage potential of natural reservoirs is required, taking into account their physical characteristics, the technical feasibility of the storage process and the associated environmental impacts.

In addition, it must be noted that leakage of carbon storage reservoirs is not considered here. We acknowledge, however, that this issue is important and should be addressed in future scenario exercises. Due to the possibility of leakage, sequestering carbon is not fully equivalent to avoiding carbon emissions and, thus, it may not have the same value. Although this point is beginning to receive attention in the literature (see e.g. Keller *et al.*, 2002, Herzog *et al.*, 2003), in particular regarding the comparison of the value of carbon capture and sequestration and that of other mitigation options, efforts are still necessary in several fronts to gain a better understanding of this issue and its implications. On the one hand, it is very important to understand the leakage characteristics of different potential reservoirs and the environmental consequences of leakage in order to assess the overall effectiveness of the storage process. On the other hand, the present economic value of future leaky sequestration should be estimated (Keller *et al.*, 2002).

3.5 An illustrative policy for the penetration of carbon capture technologies

We turn now to the description of the illustrative technology policy that has been imposed on the global fossil-fired electricity systems in the A2-CCT scenarios. Following a rise in global environmental concerns, a technology policy is introduced that enforces an increasing use of fossil-fired power plants with carbon capture. For doing so, it is assumed that these technologies must achieve a minimum pre-specified share of the total fossil-fired installed capacity. This share increases in time up to the point where all fossil-based power plants are equipped with carbon capture. The technology policy is simulated in the MESSAGE model by logistic penetration curves[7], enabling a smooth transition from unabated power generation to a regime where carbon dioxide is captured in all fossil-fired power plants in the long term.

We specify two different logistic penetration curves, one for the industrialized regions (labeled as IND) and a second curve for the developing regions (labeled as DEV). We assume that the technology policy will be introduced first in the industrialized regions (i.e., OECD90 and REF). In these regions, the share of carbon capture technologies in total installed capacity of fossil power plants is forced to increase gradually from less than 1% in 2010 up to practically 100% by 2070.

[7] This does not mean that in the model the constraint that represents the CCT policy is formulated as a logistic (i.e., non-linear) expression. The constraint in the model is linear, specifying the fraction of the total installed capacity of fossil power plants that must incorporate carbon capture in each time period, but the values assigned to such fraction in each time period follow the logistic curve described.

As for the developing regions (ASIA and ALM), we assume that they will follow with a delay of about two decades. That is, they start adopting carbon capture technologies in fossil-fired power plants in 2030. However, we assume that the diffusion takes a shorter time there and they achieve approximately 100% of adoption also in 2070. This appears consistent with historical patterns of technology diffusion discussed in the literature (e.g., Grübler, 1996), where the adoption of a technological innovation experiences a time delay between regions belonging to the core and regions in the periphery of its spatial diffusion domain. Here, we assume that the industrialized world operates as the core of the diffusion process of carbon capture technologies.

The curves are presented in Figure 1. The time required by the technology to increase its market share from 10 to 90% of its duration (Δt) is presented. With our assumptions, Δt of 26 years and 19 years result for the diffusion of carbon capture technologies in, respectively, industrialized and developing regions. Since carbon capture technologies are still in their infancy, we cannot provide an empirical justification for the parameters of the logistic curves used here, but our assumptions lie within the ranges reported in the literature for other technology diffusion processes.[8]

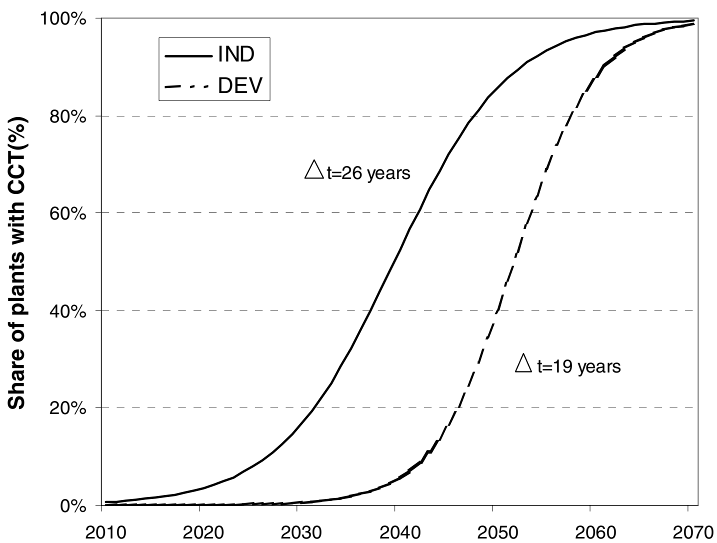

Figure 1: Logistic penetration curves assumed for the penetration of fossil-fired power plants with carbon capture technologies in the A2-CCT scenario for the industrialized (IND) and developing regions (DEV). Δt is the time in years that takes the innovation process to go from 10 to 90% of its duration.

We recognize that this is an arbitrary assumption, which imposes a somewhat fast penetration of the carbon-capture technologies, and model results are sensitive to it. However, we only intend to examine the effects of an illustrative technology policy here, without making any claim about its likelihood. In our study, we assume the introduction of a phased-in mandatory scrubbing policy on a fraction of the installed fossil fuel-fired capacity. The basis for this assumption is the general nature of existing global policies for environmental control. For instance, in the U.S. Acid Rain Program, the first Phase of the Clean Air Act is limited to 263 of the most polluting units, while the second Phase encompasses more than 2000 existing and new units across the U.S. The formulation of such a policy ensures that all major sources of pollution gradually fall under the

[8] Grübler (1996) constructed a histogram for Δt for a number of different diffusion processes using two samples. For the first sample (117 cases collected at IIASA), a mean value of 57.5 years (std. deviation 52.5) was found. For the second (265 cases, including the previous sample and cases from other sources), a mean value of 41 years (std. dev. 42) was estimated. The highest frequency was found in the range 15-30 years.

umbrella of regulation. Limiting the policy to only new sources, leads to an imbalance in both spatial and temporal reduction profiles, as many of the existing electricity plants have service lives of 30 years or more.

Note that this technology policy is imposed on the whole set of fossil-fired technologies and not on individual technologies. That is, fossil-fired technologies with CO_2 capture will compete against each other to fulfill the constraint. Thus, the resulting fossil-fired mix and the corresponding amounts of carbon sequestered by individual carbon capture technologies will depend, among other factors, on the combined effects of the costs of the different power plants and their efficiencies and the learning-curve characteristics, capture efficiencies and energy penalties of the associated carbon capture technologies.

4. Endogenizing Technological Learning for Carbon Capture Technologies

This section presents a brief description of the methodology used to endogenize technological learning for fossil power plants and carbon-capture technologies in the MESSAGE model. MESSAGE is an energy systems-engineering optimization model that disaggregates the world in a number of regions, providing a detailed technology representation of the energy systems in each of them (Messner and Strubbeger, 1995, Messner and Schrattenholzer, 2000).

We consider here the typical formulation of learning, or experience curves, describing the specific investment cost of a given technology as a function of the cumulative capacity, a proxy for the accumulated experience (Argote and Epple, 1990). The curve reflects the fact that some technologies experience declining costs as a result of their increasing adoption due to, among others, learning-by-doing (manufacturing) and learning-by-using (use) effects. The specific investment cost (SC) is formulated as:

$$SC(CC) = a * CC^{-b}$$

Where:

CC: Cumulative capacity

b: Learning index

a: Specific cost at unit cumulative capacity

Usually, instead of the learning index b the learning rate (LR), i.e. the rate at which the cost declines each time the cumulative production doubles, is specified as:

$$LR = 1 - 2^{-b}$$

For instance, a LR of 10% means that the costs are reduced by 10% for each cumulative capacity doubling. Cumulative capacity refers here to the cumulative installed MWs of power plants with carbon capture systems. Note that this is but one possibility to approximate the experience accumulated with carbon capture and sequestration systems. Other studies (Keller *et al.*, 2002) have used the cumulative amount of CO_2 sequestered instead.

As mentioned above, in a previous study a comparison of the role of carbon capture technologies when static costs are assumed and when costs trends are consistent with the learning curve concept was performed for different scenarios (Rubin *et al.*, 2001, Riahi *et al.*, 2002). For doing so, an iterative “ex-post” approach was applied that allowed an adequate emulation of learning curves. However, the costs trends still remained exogenously given.

In order to address such shortcoming in this analysis we resort to the endogenization of learning curves in the MESSAGE model. This allows the model 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 within the time horizon.[9] 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.

When the original formulation of the learning curves is included in standard linear programming models, the result is a non-linear and non-convex optimization problem. Such kind of problems possesses several local optima, and a global optimal solution cannot be guaranteed with standard non-linear optimization solvers. Thus, here, following the work of Messner (1997) and Mattsson (1997), we resort to a linearization of the problem applying Mixed Integer Programming (MIP) techniques. The MIP approach provides such linearization by a piece-wise interpolation of the cost curve. Binary variables are used to control the sequence of cost segments along the curve. Although more computational intensive, an optimal solution can be identified for this linear approximation. For a more detailed description of this approach see Messner (1997), Mattsson (1997) or Barreto (2001).

In our study we distinguish between endogenized learning curves for carbon capture technologies and for power plants. Given the fact that carbon capture technologies are still in an early stage of development, it is very difficult to assess their learning characteristics. As an approximation, the learning characteristics of scrubbing technologies for other pollutants are used.

Our assumptions rely on the work of Rubin *et al*. (2001). They conducted an estimation of historical learning rates for capital and operating cost in flue gas desulfurization (FGD) technologies used in coal-fired power plants for SO_2 capture. Such estimation was made on the basis of cumulative capacity installed in the U.S., Germany and Japan over the past three decades. These three countries dominated (and shared) inventive activities and innovations in this technology (Taylor, 2001) and, therefore, represent an adequate sample to examine the cost reductions that could be attributed to technology innovation. Among other factors, the imposition of stringent regulations regarding SO_2 control in power plants, in particular in the U.S., played a major role in pushing the development and adoption of these technologies. That is, innovation in, and diffusion of, these technologies was linked to government actions that imposed regulatory regimes creating markets for environmental control technologies. As a result of this study, a learning rate of approximately 13% was obtained and it is applied here for all learning carbon capture technologies considered in this analysis.

In order to reduce the computational burden, we just consider learning curves just for the fossil power generation technologies and the associated carbon capture systems. Cost improvements for other zero-carbon technologies are exogenously given as described above in Section 3.3.

The learning process is assumed to take place on a global scale. Although we recognize that global learning may not be consistent with a world where separate economic blocks emerge, we have chosen it here mainly for methodological reasons, since it simplifies the computational task. Under the global learning assumption, the deployment of a learning technology in a given region affects its investment costs in all of them and, as a consequence, may render it more attractive also in other regions.

Figure 2 gives an illustration of the learning curves of the carbon capture technologies considered in this analysis. Both the original nonlinear curves and the step-wise approximation used by the MIP approach are presented. For the stepwise approximation, five segments have been applied.

[9] The cost reduction potential depends, among others, on the parameters assigned to the learning curve, the maximum growth rates allowed, the maximum potential for capacity of activity of the different technologies, etc.

Similarly, the same step-wise approximation was performed for the learning curves of the reference power plants.

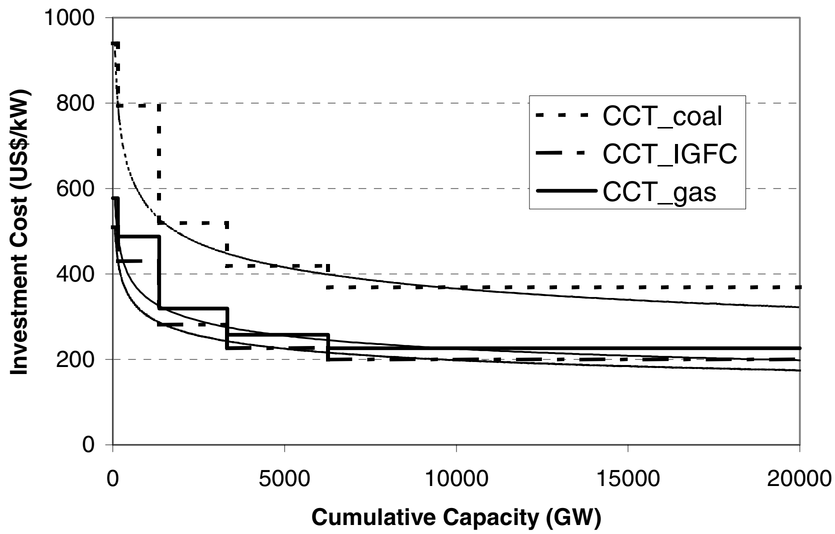

Figure 2: Learning curves assumed in this exercise for the carbon-capture clusters considered in the power sector. The step-wise approximation and the original non-linear curve are presented.

5. A2-CCT: Scenarios with Clean Fossil Power

In this section we will discuss selected results from our analysis. We will describe mainly the A2-CCT scenarios, where policy is applied, and analyze its effects in the global energy system and associated carbon emissions. For the sake of comprehensiveness we consider three different A2-CCT cases. In the first case, labeled "No Learning", the costs for the capture technologies remain constant along the time horizon. In the second case, labeled "CCT Learning", the costs for the carbon-capture technologies follow the learning curves described above, and in the third case, labeled "PPL & CCT Learning", also the costs of the fossil power plants follow learning curves. For reference purposes, a comparison with the cases without policy, the A2 scenarios (with and without learning for fossil power plants), are also presented. It should be noted that, since the characteristics of some technologies have been updated, the A2 figures presented here can be different from those reported in Riahi and Roehrl (2000) and SRES (2000). For simplicity, the discussion here is carried out mainly at the global level. Where necessary, specific results for industrialized (IND) and developing (DEV) countries are also shown. Table 7 summarizes the scenario's main global indicators.

Table 7: Basic global indicators of the A2 and A2-CCT scenarios for 2100. Historical values for the year 1990 are presented for comparison.

		A2		***A2CCT***		
		No learning	PPL Learning	No Learning	*CCT Learning*	PPL & CCT learning
	1990	**2100**		**2100**		
Population (billion)	5.3	15	15	15	15	15
GWP (trillion 1990US$, market exchange rates)	20.9	242.8	242.8	242.8	242.8	242.8
Equity ratio of income (DEV/IND[10])	0.062	0.24	0.24	0.24	0.24	0.24
Primary energy (EJ)	352	1983	1924	2061	2061	2057
Final energy (EJ)	275	1342	1337	1342	1350	1342
Electricity generation (EJ)	42	539	553	521	535	568
Annual CO_2 emissions (Gt C)	6.0	27.9	29.1	22.5	21.5	21.1
Cumulative CO_2 emissions from 2000 (Gt C)	--	1837	1908	1598	1460	1497
Cumulative sequestered CO_2 emissions from 2000 (Gt C)	--	--	--	242	284	379

5.1 Primary-energy supply

Figure 3 presents a comparison of the structural changes of the world primary-energy mix for the A2 and A2-CCT scenarios. The historical changes, shown as a reference, reflect major technology shifts, from traditional use of renewable energy to the coal age of the 19th century to the dominance of oil along the 20th century and the later emergence of natural gas.

Already in the A2 scenarios, world primary-energy consumption experiences a substantial increase, reaching approximately 2000 EJ by the end of the 21st century. While conventional oil resources remain important in the medium term, the global energy system shifts away from them in the longer term. The introduction of learning for fossil power plants in the A2 baseline leads to comparatively early upfront investments into advanced coal-fired power systems, and hence the contribution of coal is higher, particularly in the medium term (around 2050) as compared to the A2 case without learning. In the long run, coal becomes the dominant primary- energy source in both baseline scenarios, accounting for about half of the primary-energy mix in the year 2100. Other primary resources that gain importance are natural gas, biomass and nuclear energy.

With the imposition of the CCT policy in the A2-CCT scenarios, a reduction in the share of fossil resources in the global primary-energy mix occurs in the medium term. This is mainly a result of fossil-based power plants becoming comparatively more expensive than other options for electricity generation. In the second half of the 21st century, however, a "recarbonization" of the primary-energy supply of the A2-CCT scenario takes place, as other sectors switch to more carbon-intensive fossil fuels. As a result, the primary-energy path in the long term does not differ substantially from that of the A2 scenario. A more detailed discussion of these interactions is presented in Section 5.2 below.

[10] DEV stands for developing regions and IND for industrialized regions.

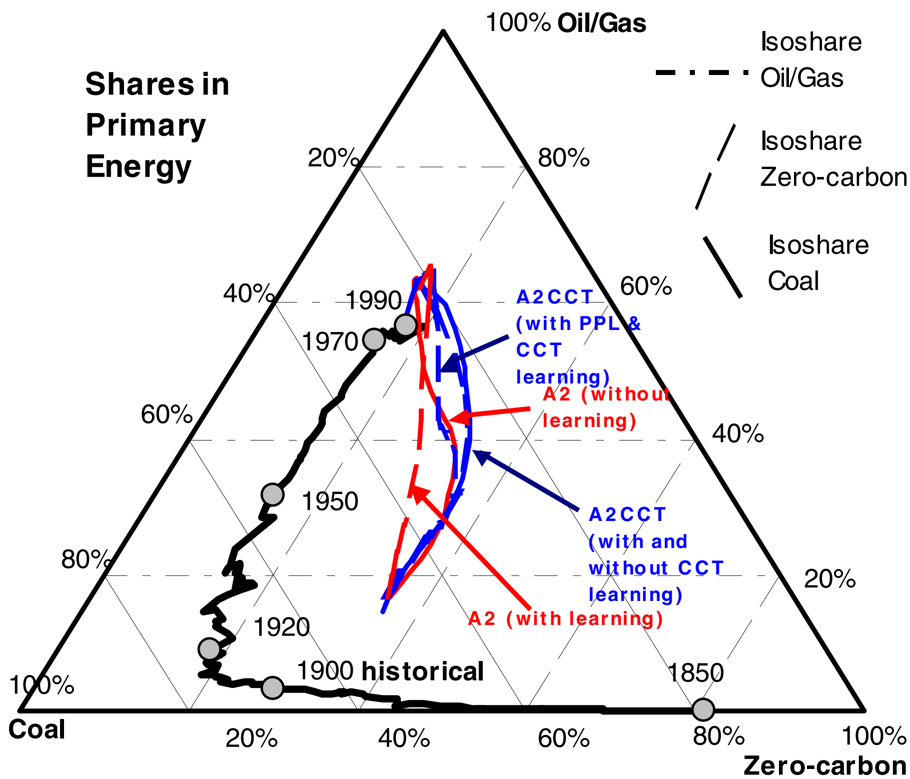

Figure 3: Global shares in primary-energy use, coal, oil/gas, and non-fossil energy, illustrated with an "energy triangle" (in percent). Constant market shares of coal, oil/gas, and non-fossil (Zero-carbon) primary sources are denoted by their respective isoshare lines. Historical data from 1850 to 1990 (black) are based on Nakićenović *et al.* (1998). The development of the primary-energy structure for the years 1990 to 2100 for the A2 and A2-CCT scenarios is shown for the years 1990 to 2100 (ten-year time steps).

5.2 Global electricity generation

Figure 4 presents a comparison of the global electricity generation in the A2 and A2-CCT scenarios for the years 2020, 2050 and 2100.[11] For fossil-fired power plants, the electricity losses due to the incorporation of carbon-capture technologies are included. In the A2 scenarios, global electricity generation increases significantly, reaching a level of around 540 to 550 EJ in the year 2100, which is about 10 times that of the year 2000 (IEA, 2002b). This growth creates a challenge for the power sector in meeting those enormous needs in an effective, clean and reliable way. But, at the same time, it provides opportunities for technological learning, driving to significant improvements of advanced electric power generation technologies.

[11] Details of the evolution of the electricity generation mix in the industrialized and developing regions are shown in Appendix 2.

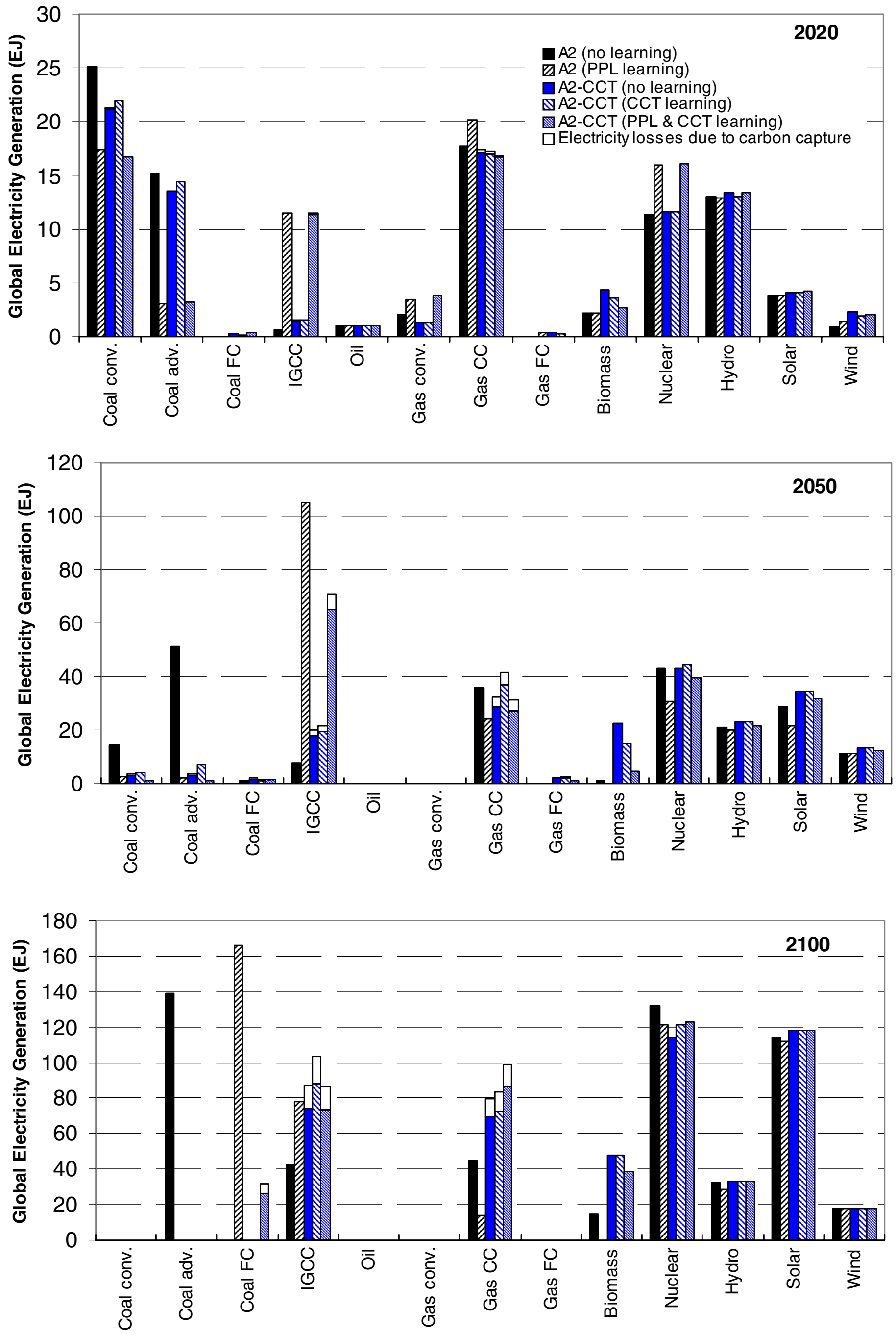

Figure 4: Global electricity generation for the A2 and A2-CCT scenarios in the years 2020, 2050 and 2100. For the A2-CCT cases, electricity losses due to the carbon capture process are shown as white bars.

In both baseline scenarios the global electricity generation portfolio remains diversified. A number of primary sources and technologies are required to meet the fast-pace consumption growth. In the case of no learning for fossil-fired technologies, they account for 50% of the generation mix in

2050 and for 42% at the end of the 21st century. The introduction of learning makes advanced fossil power generation technologies more competitive in the long run, leading to an increase of the contribution of these technologies. When learning is considered in the baseline, fossil power accounts for 60% of the total generation mix in 2050 and for 48% in 2100 respectively.

The major difference between the two baseline scenarios is, however, the evolution of the portfolio of fossil technologies. The introduction of learning for reference plants leads to the comparatively early upfront investments into advanced fossil power generation technologies. As a result, IGCC is dominating the power sector in the medium term (2050), subsequently substituted by the next generation of coal gasification plants (high temperature fuel cells) in the very long term (Figure 4). In contrast, in the baseline without learning, single steam-cycle coal technologies (supercritical) play the dominant role, and to some extent also natural gas combined-cycle power plants together with IGCC gain importance.[12] Both baseline scenarios depict a world where existing conventional coal systems are phased out along the time horizon and where highly efficient and clean coal technologies develop and diffuse, allowing coal to maintain its position as a major fuel option well into the future.

Although fossil-fired technologies, mainly based on coal, constitute a significant share of the global electricity production mix in the baselines, other technologies also achieve a significant penetration. Particularly nuclear power plants play an important role in both baseline scenarios, reaching about 25% share of the generation mix in the year 2100. Note, however, that adding learning for reference power plants increased the diffusion of nuclear technologies in the medium term. In the new scenarios there is more nuclear power in the first decades and less around the middle of the century. The increase of nuclear in the short term (2020) is due to the rapid substitution of mature fossil power plants by IGCC at initially high costs, giving nuclear a short-term competitive edge. The situation changes in the medium term (2050) when IGCC become available at relatively low costs, leading to the substitution of nuclear.

Also renewable sources increase noticeably their contribution to the global generation mix in both scenarios, reaching about 30% in the year 2100. The individual market shares of renewable technologies remain relatively small, but together they form a zero-emissions generation cluster that makes sizeable inroads. With the exception of biomass plants, the contribution of individual renewable technologies does not differ significantly across the two baseline scenarios. Adding learning to the fossil power plants, leads in our baseline scenario to the "lock-out" of biomass-fired power generation (compared to contributions of about 15 EJ in 2100 in the case of no learning).

Already in the A2 scenarios, due to the cost reductions assumed for renewable and nuclear power plants, they capture a substantial share of the global electricity production.[13] As will be seen below, the penetration of these zero-carbon technologies, among other factors, contributes in keeping the amounts of carbon dioxide captured in the fossil power sector in the A2-CCT scenario well within the ranges of geological storage potentials.

Once the CCT policy is introduced, several changes can be observed (see Figure 4). In the first place, since fossil-fired electricity generation becomes more expensive because of the necessary introduction of carbon capture technologies, fossil-based systems decrease their contribution to the global generation mix from 42-48% to 30-36% in the year 2100 (depending on the assumptions for

[12] There is also a significant difference between the deployment of NGCC in the baseline scenarios. Due to its limited potential for learning (as compared to other more advanced fossil power systems, see Table 2) NGCC loses considerable market shares in the baseline with learning.

[13] Note that the scenarios assume significant exogenous cost reductions for the majority of renewable electricity generation technologies. Endogenizing technological learning for these technologies, would most likely lead to some more diversified results. However, due to computational limitations – just a limited number of technologies can be endogenized in the full-scale MESSAGE model – endogenous technological learning was not introduced for these technologies.

learning for fossil power plants and associated capture technologies). Non-fossil technologies, particularly biomass-based gasification plants and to a smaller extent hydro and solar power plants, increase their electricity output instead. It seems that the deployment of biomass technologies is most sensitive to marginal changes in energy prices due to the CCT policy. This is partly because other renewable technologies like solar and wind benefit substantially from learning effects already in the baseline and the imputed changes in fossil electricity prices are not sufficiently high to trigger substantial additional deployment.

As mentioned above, the CCT policy is imposed on the whole set of fossil-fired power plants and, therefore, they compete against each other to fulfill it in the least-cost way. As a result, in the remaining fossil-fired share the participation of the individual technologies is modified. A comparison of the three A2-CCT scenarios shows that under the CCT policy coal-based IGCC and natural gas combined-cycle are the most robust options, significantly contributing to the power mix under all three alternative learning cases. An important finding illustrated by the A2-CCT (PPL & CCT learning) scenario is also, that considering learning for power plants leads to additional inroads for the next generation coal gasification plants with high temperature fuel cells in the very long term (2100).

Thus, with the CCT policy in place, the dominant role in the fossil-fired share of global electricity production is played by IGCC plants, which allow a more efficient and less expensive pre-combustion capture of CO_2. A complementary role is played by natural gas combined-cycle plants and coal-fired high temperature fuel cells (in the case of learning for power plants), which also allow a competitive combination of electricity production and carbon capture. Advanced supercritical coal-fired plants still play a role in the medium term, bridging the transition between today's coal-based systems and the IGCC-dominated regime, but they are phased out in the long run.

Summarizing, the changes within the fossil-fired set of technologies due to the introduction of the CCT policy in the system consist of two things: A shift towards more efficient and cost-effective coal-fired technologies like IGCC, and high temperature fuel cells and fuel switching towards less carbon-intensive fossil fuels (i.e. natural gas combined-cycle plants). Both shifts allow a competitive combination of electricity production and carbon capture.

Coal gasification technologies and the gas combined-cycle can be seen as key complementary elements of a strategy for achieving a global fossil-fired electricity generation system with low emissions of carbon to the atmosphere. Both technologies can produce electricity with high conversion efficiencies and low levels of pollutants emissions. In addition, the technologies share a number of commonalities and could profit from progress in each other (e.g. through learning spillovers). Moreover, being attractive options for electricity generation and facilitating the carbon capture process in case it becomes necessary, they represent flexible and robust choices.

Gas combined-cycle turbines are, already today, one of the most competitive electricity generation technologies and they are expected to experience additional improvements and to conquer more markets in the future. IGCC systems, however, are at a much earlier stage in their life cycle. Nonetheless, IGCC systems have a promising potential for electricity generation because they offer high fuel flexibility, significant efficiency gains 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 can produce hydrogen or other fuels or chemicals together with electricity in so-called poly-generation schemes (see e.g. NETL, 2001, Williams *et al.,* 2000). In the long term, IGCC systems or their successor technologies could become a key building block of an energy system where carbon-free hydrogen and electricity are the main energy carriers.

From today's perspective, however, ensuring that IGCC becomes competitive in the marketplace will require a number of actions. IGCC is currently in the demonstration phase and a number of technical and economic issues remain to be solved. The technology is still regarded by many power producers as too expensive and too risky an investment in comparison to conventional pulverized-coal plants. Thus, significant cost reductions are required, particularly in the gasification process. In addition, efficiencies must be increased, better gas cleaning and conditioning processes must be introduced, gas separation technologies must be developed and the utilization of process and waste streams must be optimized (Stiegel, 1998). Demonstration programs, some of them already underway, will help in gaining experience with these plants and improving their performance, thus building confidence on potential adopters of this technology.

Moreover, as shown by the scenarios, hybrid systems combining IGCC plants and high-temperature fuel cells (HTFC) could be developed and deployed. The potential for those systems has also been highlighted in the literature (e.g., NETL, 2000, Rao *et al.*, 2002). Fuel cells could, for instance, replace combustors in IGCC plants while the gas turbine system could provide the balance of plant for the fuel cell. High-temperature fuel cell systems could achieve very high conversion efficiencies and very low pollutant emissions. In addition, they could facilitate the carbon capture process and contribute in substantially reducing the corresponding "energy penalty". High-temperature fuel cells, however, must become less expensive and a number of technical problems still have to be surmounted (Srinivasan *et al.,* 1999).

In order to adequately understand the results, it is important to examine the relative prices of the resources, since they play a role in defining the technologies that are chosen by the model. Particularly important for this study are those of natural gas and coal, the main primary fossil resources in the electricity sector. Figure 5 presents the evolution of the shadow prices of coal and gas averaged across regions in the A2 and A2-CCT scenarios.

Already in the A2 scenarios, the shadow prices of both resources increase substantially within the time horizon reaching, at the end of 21st century, approximately five times the values in the year 2000. However, coal remains clearly less expensive than natural gas. With the imposition of the CCT policy, the shadow prices of natural gas increase, as compared to the A2 baseline, while those of coal remain approximately the same. The CCT policy drives to a substantially higher installation of gas-fired combined-cycle turbines and, therefore, to a higher consumption of natural gas, thus explaining the increase in its shadow prices. The behavior of the shadow prices is in line with the resulting shares of coal and gas-fired power plants in the electricity sector in the A2 and A2-CCT scenarios described above.

The imposition of the CCT policy results in higher costs of electricity production. Figure 6 presents the evolution of the global average of electricity shadow prices for the years 2000, 2050 and 2100. As shown, in the long-term, electricity shadow prices are relatively higher in the case that the CCT policy on fossil-fired generation technologies is imposed. Clearly, this effect is highest in the case where no learning is assumed and lowest in the A2-CCT scenario that assumes learning for the power plants as well as capture technologies.

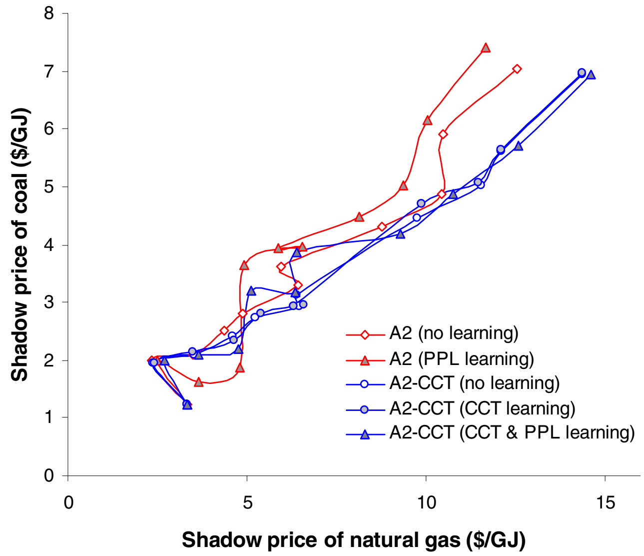

Figure 5: Comparison of the evolution of the shadow prices for natural gas and coal for the period 2000-2100 in the A2 and A2-CCT scenarios.

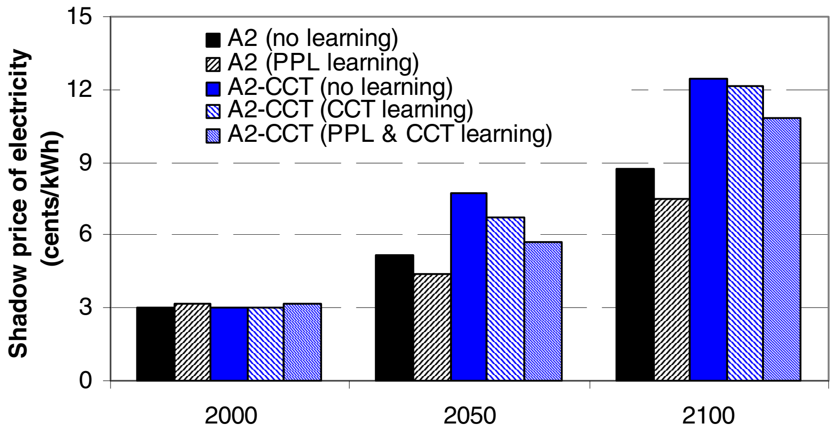

Figure 6: Shadow prices of electricity.

5.3 Carbon emissions of the electricity sector

We turn now to discuss the CO_2 emissions associated with the global fossil electricity system. Figure 7 presents the carbon emissions of the global electricity generation system, distinguishing the emissions from individual fossil-fired technologies for the years 2020, 2050 and 2100. Both released and captured emissions are presented.

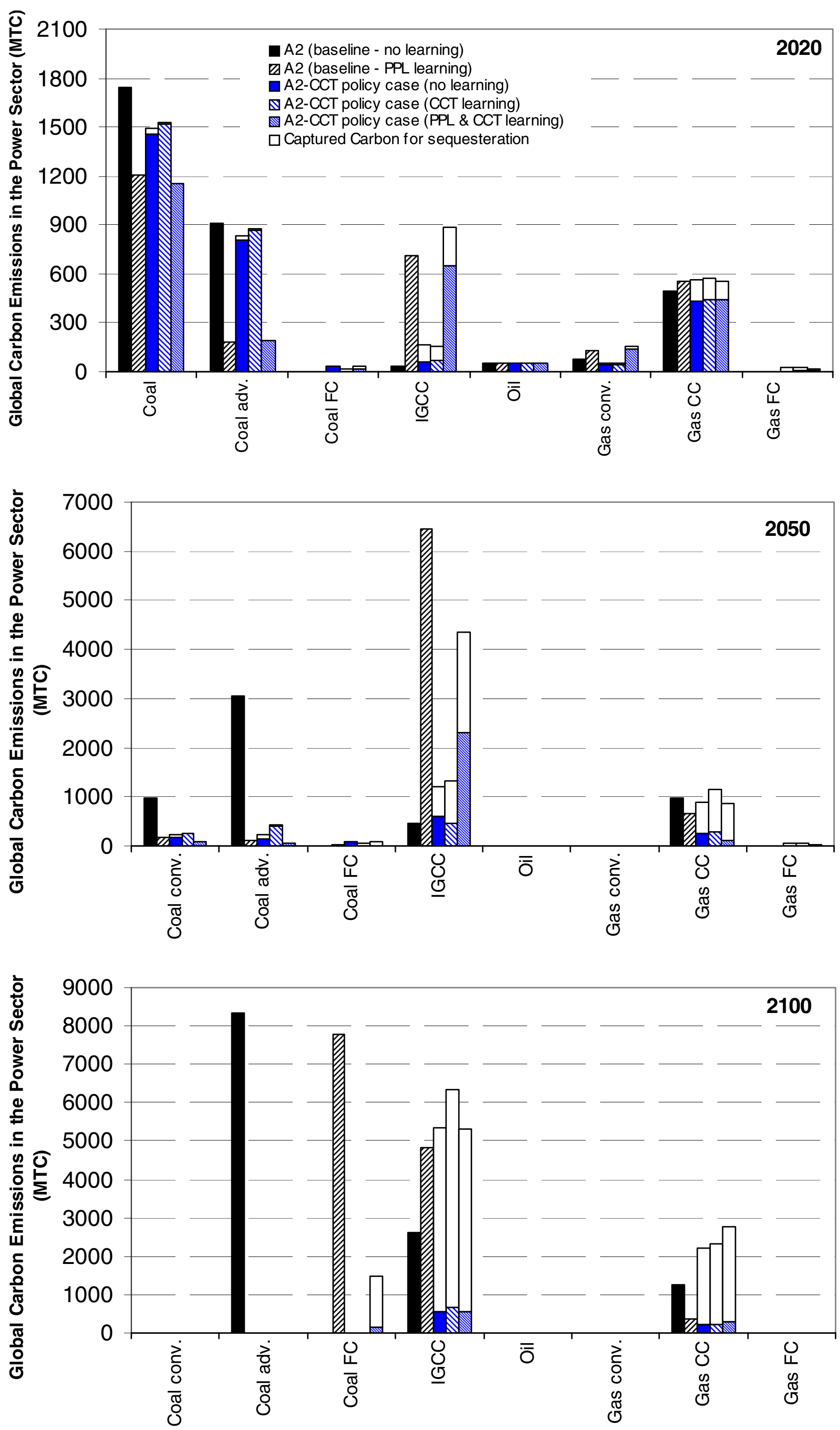

Figure 7: Global carbon emissions in the electricity generation sector by technology. The amounts of carbon captured and released are distinguished.

For all cases, with and without CCT policy, in the short term (up to 2020), today's conventional coal technologies still dominate the fossil generation mix and continue to be mainly responsible for carbon dioxide emissions within the power sector. Scenarios that assume learning for reference power plants are characterized by relatively early penetration of IGCC, substituting advanced coal (supercritical) technologies (which play a prominent role in the short term of scenarios without learning).

Clearly, in the medium and long term, the contributions of different power plants to the global emissions differ substantially in the A2-CCT scenarios compared to the A2 scenario. In the A2 scenario without learning (for power plants), supercritical coal-fired plants dominate fossil-fired electricity production and, thus, evolve to become the main emitters in the long term, reaching 8.4 Gt of carbon by the end of the 21st century. In the case with learning the power sector is dominated by coal-fired high temperature fuel cells responsible for emissions of about 7.8 GtC in 2100. Other technologies such as IGCC and NGCC also contribute noticeable amounts of carbon emissions in the baseline scenarios. By the end of the 21st century, CO_2 emissions from advanced supercritical coal plants, IGCC, gas combined-cycle turbines, and coal-fired high-temperature fuel cells account on aggregate for 13 GtC in the case with learning for power plants, and 12.2 GtC in the case of no learning. This corresponds to 45% of the scenario's total emissions in the case of learning and to 40% in the case of no learning respectively. In the A2-CCT scenarios all fossil power plants are equipped with carbon capture technologies, and hence the resulting emissions from the power sector corresponds just to 3 to 4% of the total emissions (depending on the scenarios assumptions concerning learning).

Finally, Figure 8 presents the total emissions from the electricity generation system in industrialized (IND) and developing (DEV) regions for two selected scenarios: the A2 baseline without learning and the A2-CCT case with learning for power plants as well as capture technologies. In the A2 scenario, emissions from the electricity sector in both groups of regions grow substantially within the time horizon, reaching 5.6 and 6.6 GtC by the end of the 21st century in industrialized and developing regions respectively. After the year 2080, emissions in developing regions become larger than those in industrialized regions. With the imposition of the CCT policy, emissions in both groups of regions peak and decline in the long term. Clearly, the time when emissions peak is related to our assumptions concerning the penetration of the carbon-capture technologies described above in Section 3.5, under which an early and relatively swift implementation of the CCT policy takes place. Since it is assumed that industrialized regions introduce the policy first, emissions in this group of regions peak already in 2020 at 1.6 GtC, as the CCT policy begins to have an effect on the system. As for the developing regions, their electricity-related emissions peak around 2040 at about 2 GtC and decline afterwards.

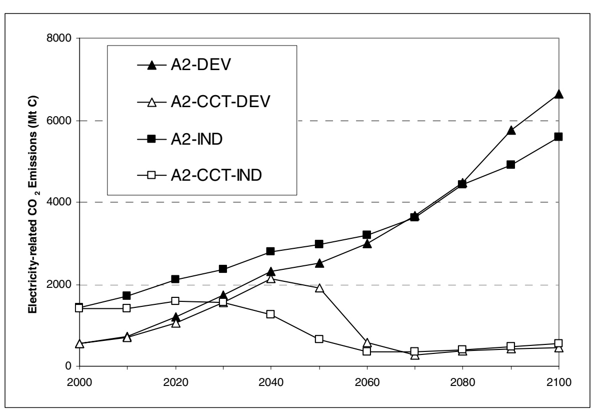

Figure 8: Electricity-related carbon dioxide emissions in industrialized (IND) and developing (DEV) regions in the A2 (no learning) and A2-CCT (PPL & CCT Learning) scenarios.

5.4 Final-energy mix

In order to better understand the effects of the CCT policy on the global energy system, it is important to examine the changes in the final-energy mix. As a reference, Figure 9 presents the evolution of the market shares of the different energy carriers in the global final-energy mix in the A2 scenario (without CCT policy).[14]

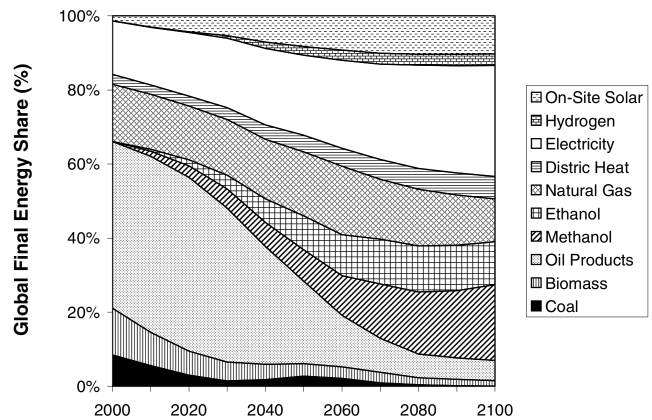

Figure 9: Evolution of global market shares of different final-energy carriers for the period 2000-2100 in the A2 scenario (without CCT policy). The baseline cases do not differ much as explained in the footnote (14).

Although, as mentioned above, coal is the dominant energy carrier in the primary-energy mix, this is not the case at the final-energy level. The scenario portrays a consistent trend towards cleaner and more convenient and flexible final-energy carriers, which continues well into the future. Therefore, direct uses of coal, together with those of biomass, disappear in the long run. Instead, coal is converted into higher quality final-energy carriers, such as electricity and liquid fuels, mainly methanol. Biomass, in turn, is converted into ethanol and electricity as well. In the long term, electricity and alcohols, together with natural gas, dominate the final-energy mix. Oil products, today's prevailing fuels, reduce their share drastically. Other energy carriers such as solar energy (on-site facilities), district heat and hydrogen play a more reduced role.

With the introduction of the CCT policy, several changes are observed. Figure 10 presents a comparison of the final-energy mix in the year 2100 for the A2 scenario without learning and two selected A2-CCT cases. Due to the introduction of the CCT policy, electricity becomes relatively more expensive, leading to price-induced changes of electricity demand, and hence, relatively lower electricity consumption in the A2-CCT cases. Also the increased use of biomass for power generation in the CCT scenarios lead to a relative price increase of this energy carrier, which reduces the demand for biomass-based liquid fuels (ethanol). In addition, the contribution of natural gas in the final-energy mix is somewhat reduced. As mentioned before, natural gas combined-cycle plants increase their production in the A2-CCT cases. Finally, since coal is being used less intensively in the power sector in the A2-CCT cases, it becomes available for other purposes. As a result, more carbon-intensive energy carriers such as oil products and coal-based methanol increase their share of the global final-energy mix.

[14] Note that there is no significant difference between the evolution of the final energy-mix in the A2 and the A2 (PPL learning) scenarios.

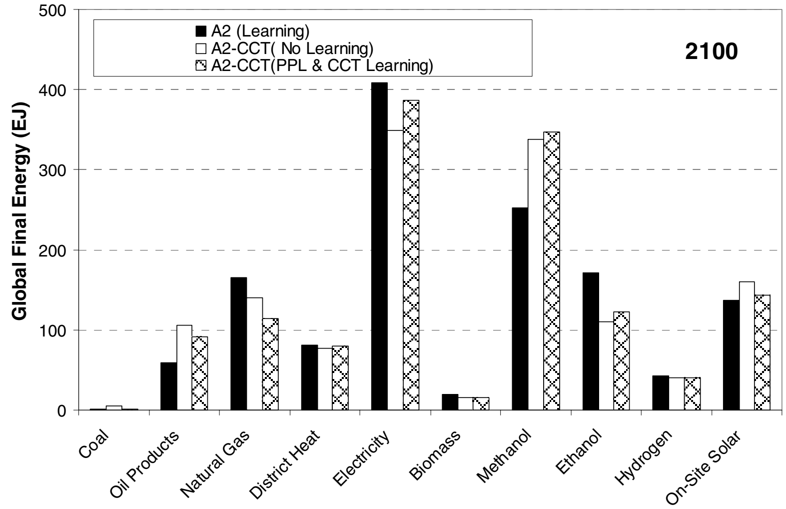

Figure 10: Comparison of the global final-energy mix in the year 2100 for the A2 (no learning), the A2-CCT (no learning), and the A2-CCT (PPL & CCT learning) scenario.

5.5 Carbon capture and storage

In this section, the contribution of the individual carbon capture technologies in the CCT policy scenarios are analyzed. In addition, we estimate the cumulative amounts of stored carbon in the A2-CCT scenarios and compare them with some estimates of storage potential in natural reservoirs available in the literature.

Figure 11 depicts the amounts of captured CO_2 along the time horizon in the A2-CCT (PPL & CCT Learning) case. Following the assumed implementation of the CCT policy, the amounts of captured carbon increase gradually along the 21st century.

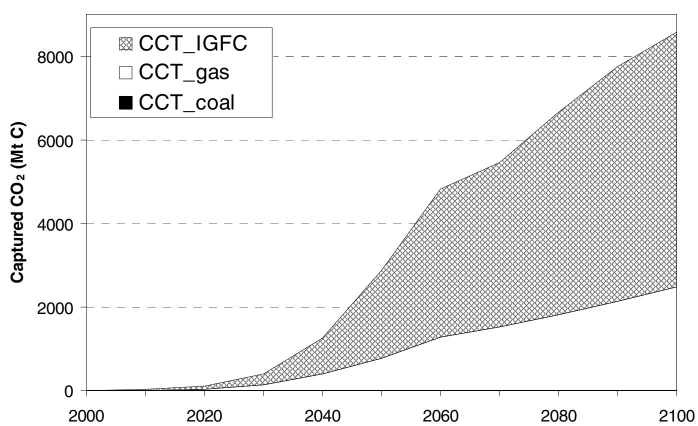

Figure 11: Captured CO_2 along the time horizon in the A2-CCT (PPL & CCT Learning) scenario. The contributions of the three CCT clusters are distinguished.

The largest amounts of carbon are captured by the CCT_IGFC technology (mainly from IGCC power plants). Smaller but still significant amounts are captured by the CCT gas technology (from gas-fired combined-cycle turbines). As conventional coal-fired power plants are displaced from the global generation mix, the capture technology associated to them (CCT_coal) plays no role in the A2-CCT scenario with full learning. Note that this technology cluster plays also just a marginal (transitional) role in the other CCT scenarios (see for a comparison Figure 7). In the long term, pre-combustion systems in IGCC and coal-fired high temperature fuel cells, offering lower additional costs and energy penalties and a more convenient CO_2 separation approach, dominate the carbon capture mix.

In our perfect-foresight cost-minimization framework, the model endogenously chooses those pairs of power plants and carbon capture technologies that provide an optimal combination between costs and efficiencies of electricity generation and carbon capture process. Also in the real world, there is a strong complementarity between carbon capture technologies and fossil-based electricity generation plants. Since the technology choice for fossil power generation becomes critical for achieving carbon dioxide separation in an efficient and cost-effective manner, and since the imposition of carbon-capture requirements may lead to significant changes in the characteristics of power-plant designs, their evolutions developments are likely to be intertwined.

The cumulative storage requirements in two selected A2-CCT scenario (no learning case, and the PPL & CCT learning case) from the periods 2000 to 2020, and 2050 to 2100 respectively are shown in Figure 12. Notice that although the amounts of carbon dioxide captured by each technology differ between the learning and no-learning cases they both provide the same ranking of carbon capture technologies in our particular study. As also shown in Figure 12 the cumulative storage is considerably higher in the case of learning.

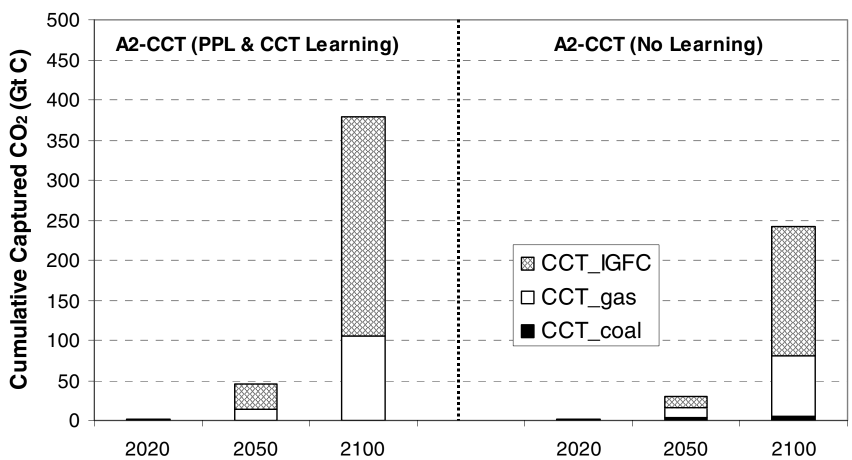

Figure 12: Cumulative amounts of captured CO_2 in the A2-CCT scenario (PPL & CCT learning case on the left side and no-learning case on the right side). The contributions of the three CCT clusters are distinguished.

As mentioned above, in our modeling study we did not impose bounds on the amount of carbon that could be sequestered. It seems then instructive to compare the cumulative carbon sequestration figures in the A2-CCT scenario with some available estimates of global CO_2 storage potentials. Only preliminary estimates of these potentials have been made (see e.g. Herzog, 2001, IEA, 2001, 2002a) and there are still huge uncertainties about the plausible ranges.

Although alternatives for storing CO_2 in solid form via e.g., mineral fixation exist, we deal here only with the options for direct sequestration of CO_2 into geological reservoirs and the ocean (NCCTI, 2002, IEA, 2001, 2002a). Geological storage options fall into two main categories: Nearterm opportunities in depleted oil and gas fields and unminable coal seams and long-term opportunities in deep saline aquifers. The latter appear to offer a potentially much larger storage capacity than the former. As for the ocean, already the primary natural sink for atmospheric CO_2, it appears to have the largest additional storage capacity of all options. However, the ocean storage process seems to be much more complex. Also, its potential environmental impacts could be huge and are not yet well understood (IEA, 2002a). Thus, it is still a controversial alternative. Table 8 presents the preliminary ranges proposed by IEA (2001). Four categories are presented. The first three of them correspond to geological storage options and the last to ocean storage.

When the cumulative amounts of stored carbon obtained in the A2-CCT scenarios are compared to the potentials in Table 8, it can be seen that they lie somewhat above the estimate for storage potential in depleted oil and gas fields but well below the upper estimate for deep saline reservoirs.

Table 8: Global carbon storage capacity of natural reservoirs (in GtC) following estimates of IEA (2001) and cumulative stored carbon in the A2-CCT scenarios (PPL & CCT learning, CCT leaning, and no learning cases).

Storage Option	Global Capacity (GtC)		
Depleted oil and gas fields	250		
Deep saline reservoirs	110-2700		
Unminable coal mines	> 4		
Ocean	> 1400		
	PPL & CCT learning	CCT learning	no learning
Cumulative stored carbon in the A2-CCT scenarios (2000-2100), GtC	379	284	242

5.6 Global carbon emissions

The global energy-related CO_2 emissions resulting in the A2-CCT cases are compared to those of the A2 scenarios in Figure 13. Without the introduction of the CCT policy, energy-related carbon emissions follow a fast growth path reaching globally around 28 GtC at the end of the 21st century. This represents about a five-fold increase as compared to the emissions of the year 1990. Note that the introduction of learning in the baseline scenario leads to higher deployment of fossil fuels in the electricity sector (as compared to the baseline without learning). This in turn, leads to an increase of fossil-fuel prices, pushing the demand for non-electric renewable energy in other sectors. Hence, some of the emissions increase in the power sector is compensated by additional decarbonization taking place in the non-electric sectors. On aggregate, this effects that the baseline emissions in the case with and without learning do not differ significantly in the long run.

With the CCT policy in place, carbon emissions reach levels between 23.2 and 24.5 GtC in the year 2100 (depending on the assumptions for learning in the power plants and the carbon capture technologies). That is, the imposition of the policy leads to a net emissions reduction of about 6 GtC in the year 2100, corresponding to about 20% of the total baseline emissions.

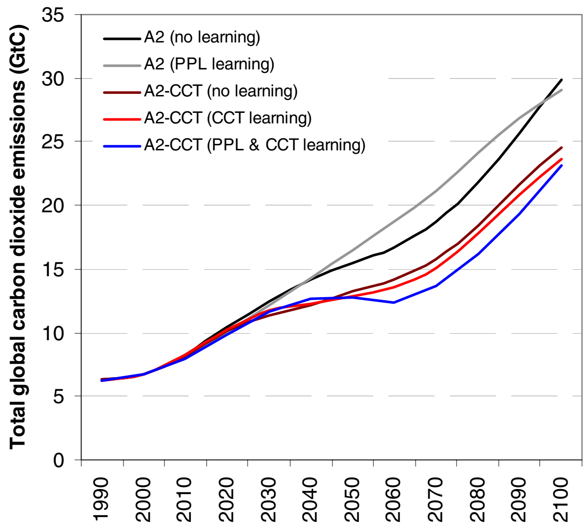

Figure 13: Evolution of the global energy-related carbon dioxide emissions in the A2 and A2-CCT scenarios for the period 1990-2100.

This net emissions reduction in the A2-CCT scenarios results from the interaction of two factors, namely the capture and sequestration of CO_2 in the fossil-fired power sector and the decarbonization/recarbonization effects that the policy triggers in the electricity sector and other energy sectors. Figure 14 shows a decomposition of the factors that influence the difference in emissions between the A2 and A2-CCT scenarios for the years 2050 and 2100. In order to keep the analysis simple and transparent, we have selected the A2 (no learning) scenario as the baseline and compare sources for emissions reductions (structural change & carbon capture) for two selected A2-CCT scenarios (no learning case, and the PPL & CCT learning case).[15]

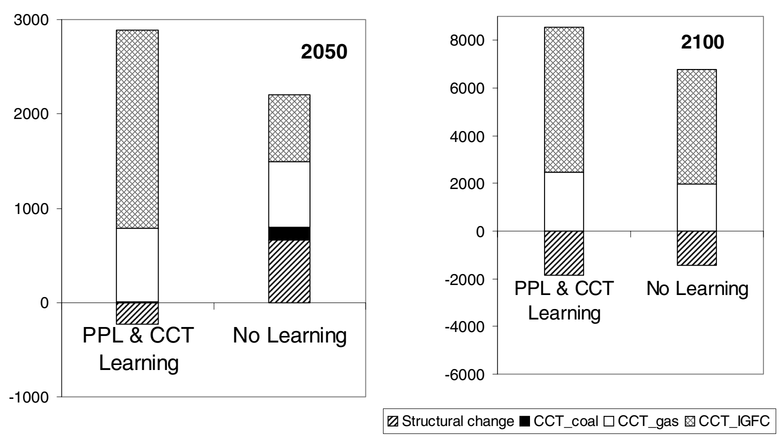

Figure 14: Contribution of carbon capture and sequestration and structural changes in the energy system to the net CO_2 emissions reduction in the A2-CCT (no learning, and PPL & CCT learning) scenarios relative to the A2 scenario without learning, in MtC.

[15] The same conclusions would apply (although exact numbers would differ) if we used the A2 (PPL learning) scenario instead of the A2 (no learning), or the A2-CCT (CCT learning) instead of A2-CCT (PPL & CCT learning).

Clearly, the factor with the largest influence in the emissions reduction is the capture and sequestration of CO_2 from fossil-fired power plants. The amount of captured and sequestered carbon dioxide increases along the time horizon as the CCT policy becomes more stringent, amounting to approximately 8.6 GtC in the year 2100 in the case with full learning (PPL & CCT). However, this emission reduction is reinforced/compensated by other structural changes in the global energy system.

Those structural changes can be separated as those occurring within the electricity sector and those outside the electricity sector. As discussed above, since the policy makes fossil-fired power plants more expensive, they lose market shares against renewable-based electricity generation. As a result, an additional decarbonization of the global electricity system takes place. Since the costs of fossil electricity generation is higher in the CCT cases without learning, this additional decarbonization effect is more pronounced in the CCT scenarios without learning (see e.g., the additional decarbonization of the A2-CCT (no learning) scenario for the year 2050 in Figure 14).

There are also structural changes triggered by the CCT policy in sectors other than electricity production. Although changes are different in different sectors (see Table 9 below), the net effect is mainly one of recarbonization, since a larger consumption of more carbon-intensive fossil fuels occurs in other energy supply and end-use sectors (in the CCT scenarios as compared to the baseline). This is a consequence of two main factors. On the one hand, it is a result of the more expensive electricity production that drives the substitution of other energy carriers for electricity at the final-energy level described above. On the other hand, it is a consequence of the changes in the electricity system favoring less carbon-intensive energy carriers (i.e. biomass and natural gas), which makes their availability for other purposes (direct use in the case of natural gas and conversion to ethanol in the case of biomass) lower. In contrast, there is a higher availability of other energy carriers, which are used less in the electricity sector (i.e. coal and oil products). Thus, a substitution of electricity, ethanol and natural gas by coal-based methanol and oil products takes place at the final-energy level.

In the case that no learning for fossil power plants and capture technologies are assumed the increase of fossil electricity prices are more pronounced than in the case of learning. Hence, in the first half of the 21st century, the additional decarbonization of the electricity system (due to the relatively higher contribution of renewable/nuclear power technologies) dominates over the recarbonization in other sectors. On aggregate, this leads (in the case that no learning is assumed) to total CO_2 emissions reductions in the year 2050 that are larger than the amount of captured and sequestered carbon (see Figure 14). Due to the relatively lower generation costs of fossil electricity, the additional decarbonization effect in the electricity sector is less pronounced in the scenario with PPL & CCT learning. Hence, the recarbonization effect in the non-electric sector is dominating already in 2050, leading to the leakage of CO_2 emissions from the electricity sector to non-electric sectors.

In the second half of the century, the final result of these structural changes is in both scenarios (with & without learning) that the decarbonization trend of the electricity sector is offset by the increased emissions in other sectors. By the end of the century, the ensuing recarbonization trend makes the CCT policy less effective. That is, the net carbon emissions reduction is lower than the amount of captured and sequestered CO_2.

In order to understand better the effects of the CCT policy in other energy sectors, a more detailed examination of the contribution of different sectors to the global carbon dioxide emissions is presented in Table 9. The carbon dioxide emissions in the A2-CCT scenario (PPL & CCT learning) are presented according to the sector where they are originated for the years 2000, 2020, 2050 and 2100. In parenthesis, the changes relative to the A2 scenario (no learning) are presented (in percent). The emissions are illustrated for three main categories in the energy supply side and for the main end-use sectors where direct use of fossil fuels occurs.

On the supply side, the main changes are noticeable in the electricity and synthetic fuels production sectors. As discussed above, emissions from the electricity generation sector are strongly reduced as a consequence of the carbon capture policy. In contrast, the emissions associated with synthetic fuel production increase, mainly due to the shift away from biomass-based ethanol towards fossil-based methanol. As for the emissions associated to the direct use of fossil fuels as final-energy carriers, the most pronounced changes occur in the transportation sectors, where the decline in the use of oil products becomes less steep under the A2-CCT policy.

Table 9: Disaggregation of CO_2 emissions by sectors in the A2-CCT (PPL & CCT learning) scenario. Changes relative to the A2 (no learning) scenario are presented in parenthesis.

	2000	*2020*	*2050*	*2100*
Energy Supply/Transformation, MtC				
Electric Generation	1999 (0%)	2645 (-19%)	2566 (-49%)	989 (-90%)
Synfuels Production	0 (0%)	356 (12%)	1964 (20%)	8985 (32%)
Other conversion*	688 (0%)	952 (-5%)	1335 (-25%)	3528 (-26%)
Direct Use of Fossil Fuels by Sector, MtC				
Residential/Commercial	910 (0%)	1221 (0%)	1507 (-3%)	919 (0%)
Industry	1191 (0%)	1461 (2%)	1259 (-1%)	1645 (4%)
Transportation	1597 (0%)	2507 (0%)	2868 (-1%)	5038 (20%)
Feedstocks	374 (0%)	739 (0%)	1315 (0%)	2084 (5%)
TOTAL emissions, MtC	6759 (0%)	9880 (-6%)	12814 (-17%)	23187 (-22%)

* Other conversion includes emissions from district heat production, energy transmission/distribution, oil refining, fuel extraction and other conversion-losses.

6. Conclusions

This report has examined the role of fossil-fired power plants equipped with carbon capture storage systems in a coal-intensive long-term scenario of the global energy system. Assuming the introduction of a technology policy that requires over time an increasing fraction of fossil-fired power generation to incorporate carbon capture technologies, we have examined the potential contribution that this option could offer in reducing energy-related carbon emissions at the global level and highlighted some of the technologies that may play a role in achieving this goal. The analysis has been carried out with the systems engineering model MESSAGE, considering endogenous technological learning for fossil power plants and carbon capture technologies, such that they experience cost reductions as a function of accumulated capacity installations.

With the imposition of the CCT policy on the global electricity system, significant changes take place in the fossil-fired share of the generation mix. Technologies are chosen, that provide the most cost-effective combination between electricity generation and carbon capture. Specifically, integrated gasification combined cycle (IGCC) plants appear as the most attractive option in the long run. Besides them, coal-fired high-temperature fuel cells and natural-gas combined-cycle plants with high conversion efficiencies, also play an important role in the policy constrained A2-CCT worlds. These results, of course, remain dependent, among others, on our assumptions about the learning characteristics of both carbon capture technologies and power plants and the methodological treatment of technology learning in the model.

The CCT policy has additional effects within the electricity system and in other energy sectors. Within the power generation sector, the policy makes fossil-fired power plants less competitive and leads to an additional penetration of non-fossil generation technologies (additional decarbonization). In the non-electric sectors, the imposition of the CCT policy leads to an increased use of more carbon-intensive fossil fuels (recarbonization). This is predominantly due to (1) the higher costs for electricity production, which drive the substitution of electricity by other carbon-intensive energy carriers at the final energy level, and (2) the changes in the electricity system favoring less carbon-intensive energy carriers (e.g. biomass and natural gas), reducing their availability, and hence, also their use in other non-electric sectors. On aggregate, the decarbonization trend in the electricity sector is partially offset in the long term by the increased emissions in other sectors. This in turn leads to the leakage of CO_2 emissions from the electric to non-electric sectors, making the CCT policy less effective.

Clearly, carbon capture and sequestration is but one of many possible alternatives for reducing the carbon-intensity of the global electricity generation system. These technologies will have to prove effective and competitive with other options such as, renewables, nuclear power, and efficiency improvements, if they are to become part of an integrated GHG mitigation strategy. Nevertheless, fossil-based power plants are going to play a significant role well into the future, even if a transition to a post-fossil energy system takes place at very high pace. Given this fact, it appears worth ensuring that the fossil-based systems that would bridge such transition are as clean as possible, as to minimize their environmental effects.

Often carbon capture and other zero-carbon technologies are seen as competing and mutually excluding options. We believe, however, that in a carbon-constrained world the penetration of both technologies could play complementary roles, permitting to achieve carbon mitigation in a more effective and efficient manner. Carbon capture and sequestration could operate as a “bridging” option during the transformation towards a post-fossil energy system, where renewable and nuclear (fission and/or fusion) technologies could play an important role in the long-term. Stimulating the learning process of both options simultaneously could contribute in hedging the risk that the introduction of carbon capture technologies reinforce the current fossil “lock-in” of the global energy system.

The results of the A2-CCT scenarios portrayed here highlight the importance of stimulating the development and deployment of fossil-fired electricity generation technologies that are able to capture carbon dioxide in a convenient and efficient way. Our analysis shows that the introduction of a policy for carbon capture and storage would foster the penetration of advanced and more efficient power generation technologies. In particular, coal gasification systems such as, IGCC power plants and high temperature fuel cells, and in addition gas-fired combined cycle power plants appear as the most attractive fossil-fired electricity generation options.

A decisive factor for the choice of the future power generation technology (in a carbon-constrained world) is the cost and efficiency of the associated carbon capture process. The important role played by the various possible combinations of fossil-based power plants and carbon capture technologies highlights also the importance of exploring ways to fully integrate carbon capture systems into future generations of fossil power plants. Including carbon capture considerations directly from the conception and design stages of the power plants would help increasing the effectiveness and reducing the costs of the process. While developments in fossil power plants and carbon capture technologies may appear independent today, they could be intertwined in the long term. Requirements for carbon capture will certainly affect the design and choice of power generation technologies in the future, as carbon capture evolves from its current status of an “add-on” technology towards a “built-in” feature. In the long-term, such interconnected technology evolution could lead to the deployment of new generations of clean and more versatile fossil-based technologies.

Carbon-capture technologies, and the electricity generation technologies most compatible with them, however, still require significant performance and costs improvements as to become a viable and competitive option. Among others, the energy requirements of the capture processes must be substantially lowered and more convenient ways for generating a concentrated stream of CO_2 are required. Also, in order to attain effective pre-combustion carbon capture in the long run, IGCC power plants (and high-temperature fuel cells) have to overcome a number of current technical barriers and reduce costs as to become competitive in the marketplace.

In order to achieve the necessary improvements, the technologies within a "carbon capture cluster" in the power sector would require policy measures to support their learning processes, i.e. to cover the "learning investments". Sustained efforts in Research, Development, Demonstration and Deployment activities (summarized as RD3, following PCAST, 1999) are required. Research and development needs have been identified in a number of areas (IEA/CERT, 2002). However, "demand pull" actions will also be necessary. While some demonstration projects are already in place, additional efforts are required, in particular concerning large-scale demonstration facilities where the different technologies can be adequately integrated. In this respect, business-government partnerships would constitute a very valuable instrument. In addition, niche markets for carbon capture and sequestration systems exist, for instance, in connection with the injection of captured CO_2 to enhance the recovery of fossil resources (Socolow, 1997), and it would be worth exploring and tapping them.

As illustrated by the scenarios presented in this report, the decarbonization of the electricity sector through carbon capture and sequestration would lead to significant CO_2 emissions reductions in the order of magnitude of about one fifth of total emissions. These emissions reductions, however, will not be sufficient for the stabilization of CO_2 concentrations. In all policy cases the long-term emissions path is dominated by increasing contributions from non-electric sectors, leading to continuous growth of emissions particularly in the second half of the century. Thus, we conclude that the long-term stabilization of CO_2 concentrations needs additional measures and a broad portfolio of technologies, ranging from energy efficiency improvements to structural changes in both the energy supply and the demand side.

Still, the contribution of carbon capture and sequestration systems to a greenhouse gases mitigation strategy could be significant, provided a number of issues related to the process of capturing, transporting and sequestering carbon could be resolved. As mentioned above, carbon capture technologies must become less energy-intensive, more cost-effective and allow a more efficient capture of CO_2. In addition, a better assessment of the sequestration potential of different reservoirs, their leakage characteristics and associated risks and costs is required. In other words, possible environmental impacts of sequestration and leakage must be quantified and the effectiveness of the overall storage schemes will have to be evaluated. Instrumental in this process will be the development of methods for Measurement, Monitoring and Verification (MMV), providing a better understanding of the fate, in the long run, of stored CO_2, thus rising public confidence in carbon capture and sequestration (NCCTI, 2002).

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Appendix 1. Aggregate technologies in the electricity generation sector

Abbreviations:	Technology Description
Coal_Stdu	Aggregation of various types of traditional (single steam cycle) coal power plants without FGD and DENOX. Some potential for district heat co-generation. Efficiencies for the model base year (1990) range between 38 and 40%. Plant life is 30 years and plant factor (availability of utilization) 65%.
Coal_Stda	Aggregation of various types of traditional (single steam cycle) coal power plants with FGD up to 90% and DENOX up to 50%. Some potential for district heat co-generation. Efficiencies for the model base year (1990) range between 38 and 40%. Plant life is 30 years and plant factor (availability of utilization) 65%.
Coal_Adv	Supercritical coal plant. Efficiencies for the model base year (1990) range between 40 and 42%. Plant life is 30 years and plant factor (availability of utilization) 65%.
CoalIGCC	Integrated (coal) gasification combined cycle with 99% FGD and DENOX. Some potential for co-generation. Initial efficiency in the base year (1990) is 43% plant life is 30 years and plant factor 65%
Oil	Aggregation of various types of oil power plants (includes e.g., Rrankine cycle with low NOx emissions and 90% DENOX, but also light oil fueled engine plants). Some potential for co-generation. Initial efficiency in the base year (1990) ranges between 40 and 46%, plant life is 30 years, plant factor 65%.
GasStd	Standard natural-gas power plant (Rankine cycle) with district heat co-generation. Initial efficiency in the base year (1990) is 40%, plant life is 30 years and, plant factor 65%.
GasCC	Natural gas combined cycle power plant including some potential for co-generation. Initial efficiency in the base year (1990) is 50%, plant life is 30 years and plant factor 65%.
GasReinj	Natural-gas combined cycle power plant with zero carbon emissions. CO_2 is assumed to be re-injected in gas or oil fields (e.g., for enhanced recovery). Efficiency loss due to re-injection (compared to GCC) about 1%. Plant life is 30 years and plant factor 65%.
Fossil FC	Coal- and gas-based high temperature fuel cell. Efficiency is 50%, plant life 25 years and plant factor 65%. It is assumed in most of the scenarios that this technology will be available commercially after 2010.
Waste	Standard municipal waste power plant (Rankine cycle) with 90% FGD and 50% DENOX. Initial efficiency in the base year (1990) is 29%, plant life is 30 years and plant factor 65%.
BioSTC	Biomass power plant (single steam cycle) with some potential for district heat co-generation. Initial efficiency in the base year (1990) is 29%, plant life is 30 years and plant factor 65%.
Bio_GTC	Biomass gasification power plant. Initial efficiency in the base year (1990) is 46%, plant life is 25 years and plant factor 65%.
Nuc_LC	Low-cost conventional nuclear power plant (light and heavy water reactor). Initial thermal efficiency in the base year (1990) is 30%, plant life is 30 years and plant factor 70%.
Nuc_HC	High-cost conventional nuclear power plant (light and heavy water reactor). Initial thermal efficiency in the base year (1990) is 35%, plant life is 30 years and plant factor 75%.
Nuc&0_carb	Aggregation of various types of advanced nuclear power plants including high-temperature and fast-breeder reactors with some potential for district heat and hydrogen co-generation. Initial efficiency ranges between 40 and 45%. Plant life is 30 years and plant factor 75%.
Hydro	Aggregation of various types of hydroelectric power plants. Low and high-cost plants are distinguished in all scenarios in order to reflect the influence of different sites and other factors on the plant costs. Plant life is 60 years and plant factor 50%.
SolarTh	Solar thermal power plant with storage and some potential for district heat and hydrogen co-generation. Plant life is 25 years and plant factors differ significantly across world regions ranging from 10 to 50%.
SolarPV	Solar photovoltaic power generation excluding onsite electricity production (predominantly large-scale power plants). Plant life is 25 years and plant factors differ significantly across world regions ranging from 10 to 50%.
Wind	Wind turbine power plant. Plant life is 25 years and plant factor 25%.
Geothrm	Geothermal power plant. Plant life is 30 years and plant factor 70%.
H2FC	Aggregation of types of hydrogen fuel cells for industrial and residential use with some potential for district heat co-generation. (Note that explicit assumptions for investment costs are not part of the MESSAGE model for all end-use technologies including these types of hydrogen fuel cells. Consequently, it was not possible to include the H2FC fuel cells in the comparison of investment costs.)
PV-onsite	Photovoltaic onsite electricity production.

Appendix 2. Electricity generation and associated CO_2 emissions in industrialized and developing regions

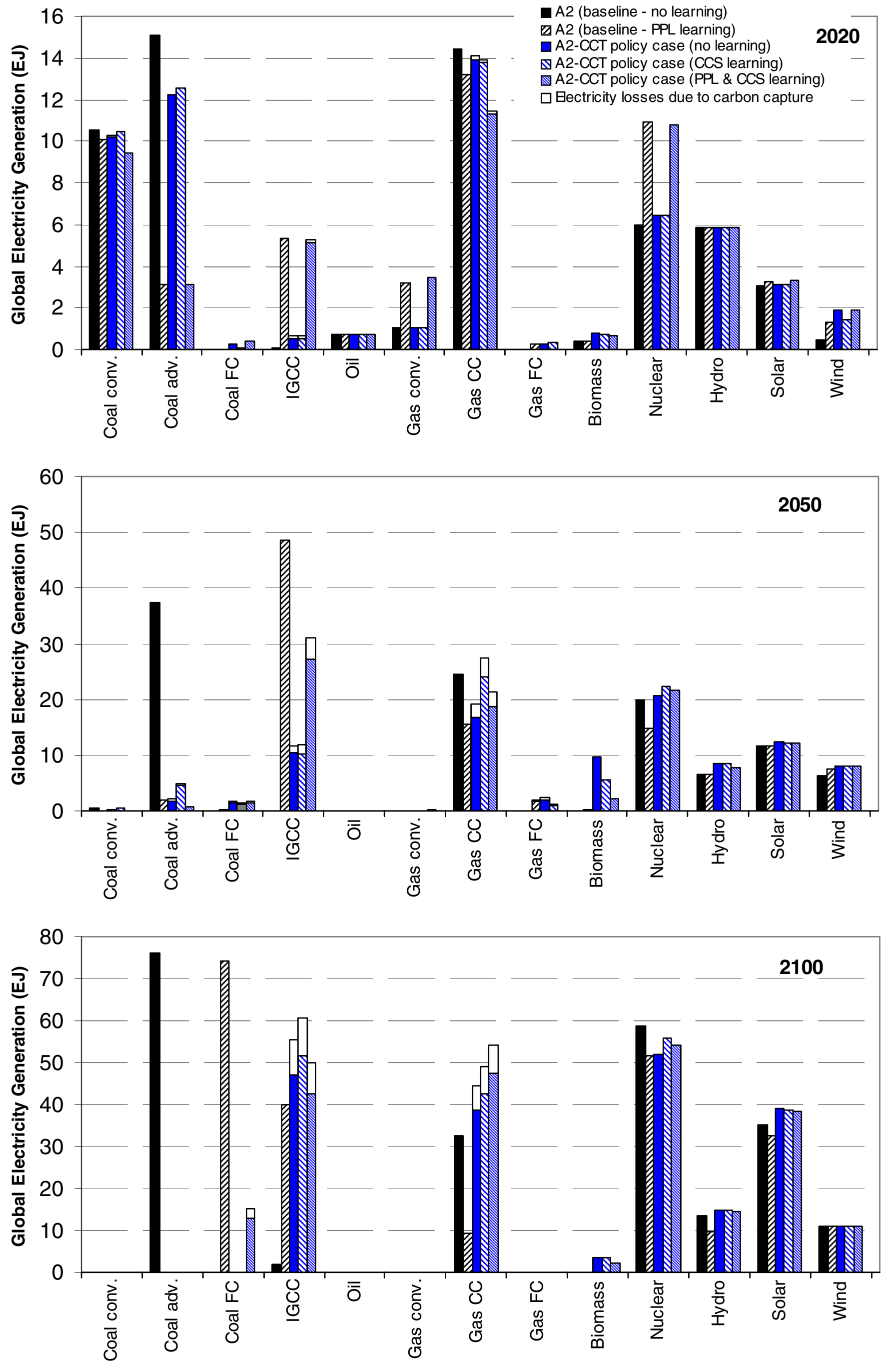

Figure 15: Electricity generation in the industrialized regions for the A2 and A2-CCT scenarios in the years 2020, 2050 and 2100. For the A2-CCT cases, electricity losses due to the carbon capture process are shown as white bars.

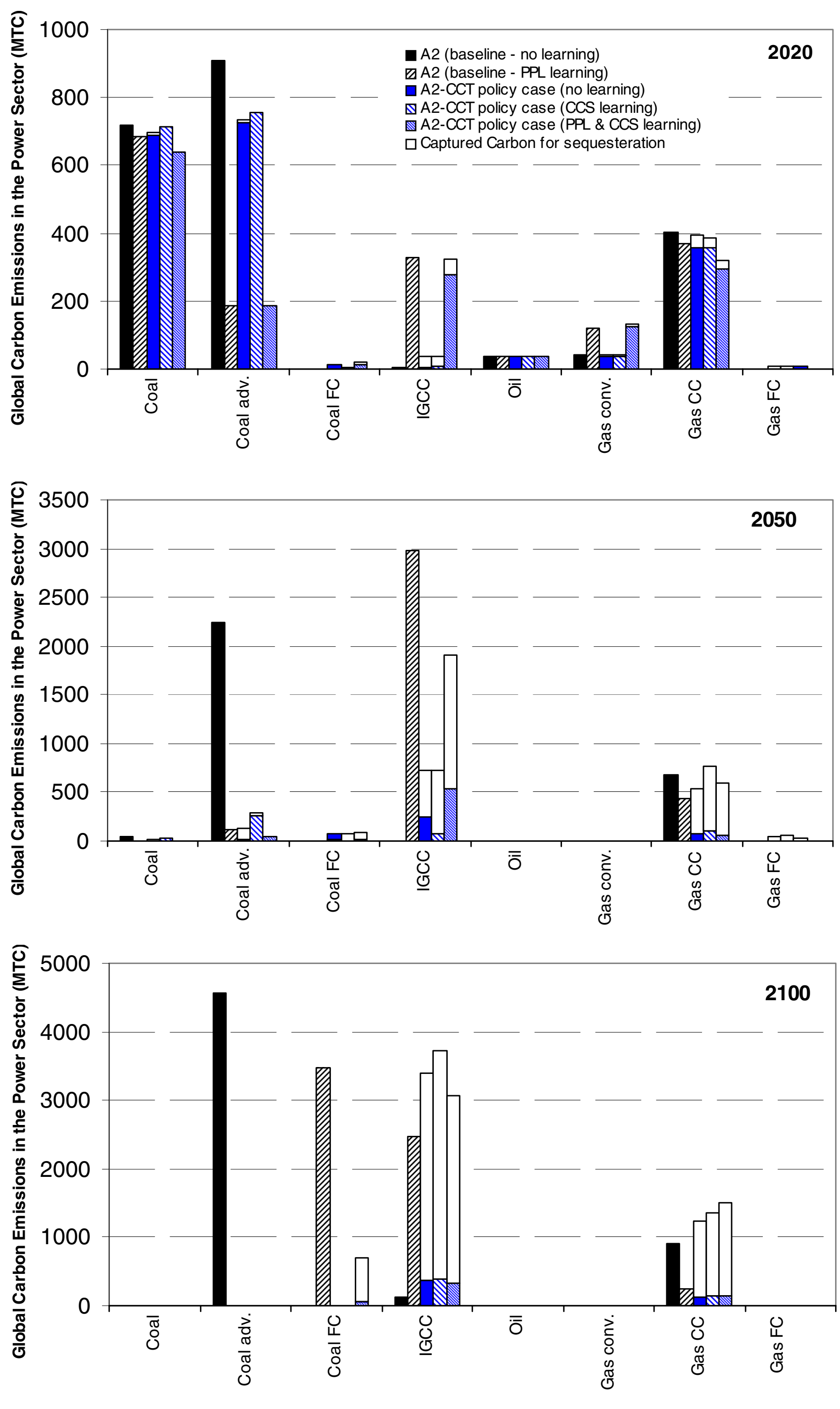

Figure 16: CO_2 emissions from the electricity generation in the industrialized regions for the A2 and A2-CCT scenarios in the years 2020, 2050 and 2100.

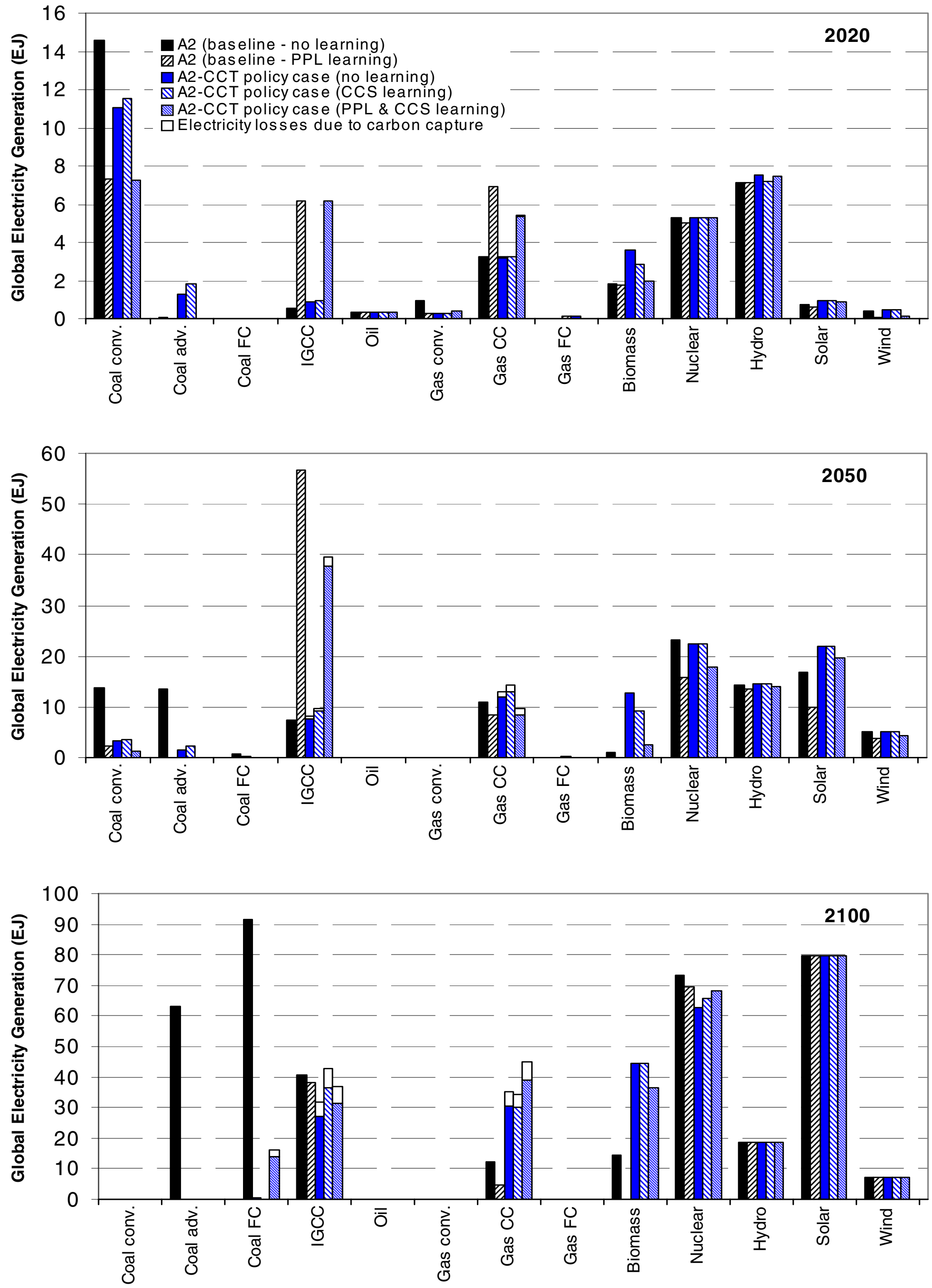

Figure 17: Electricity generation in the developing regions for the A2 and A2-CCT scenarios in the years 2020, 2050 and 2100. For the A2-CCT cases, electricity losses due to the carbon capture process are shown as white bars.

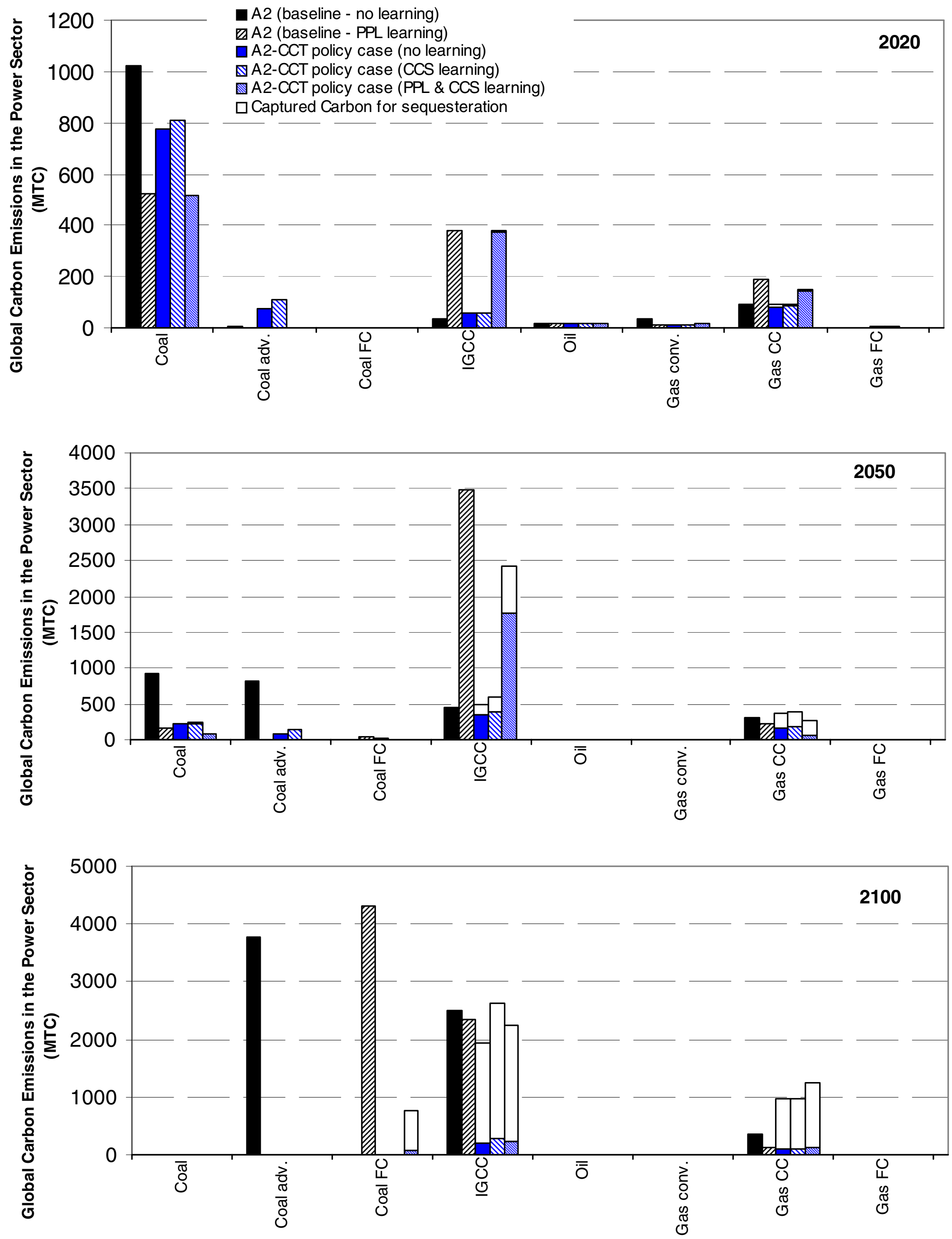

Figure 18: CO_2 emissions from the electricity generation in the developing regions for the A2 and A2-CCT scenarios in the years 2020, 2050 and 2100.