MIT Joint Program on the Science and Policy of Global Change

Directed Technical Change and the Adoption of CO_2 Abatement Technology: *The Case of CO_2 Capture and Storage*

Vincent M. Otto and John Reilly

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Abstract

This paper studies the cost effectiveness of combining traditional environmental policy, such as CO_2 trading schemes, and technology policy that has aims of reducing the cost and speeding the adoption of CO_2 abatement technology. For this purpose, we develop a dynamic general equilibrium model that captures empirical links between CO_2 emissions associated with energy use, directed technical change and the economy. We specify CO_2 capture and storage (CCS) as a discrete CO_2 abatement technology. We find that combining CO_2-trading schemes with an adoption subsidy is the most effective instrument to induce adoption of the CCS technology. Such a subsidy directly improves the competitiveness of the CCS technology by compensating for its markup over the cost of conventional electricity. Yet, introducing R&D subsidies throughout the entire economy leads to faster adoption of the CCS technology as well and in addition can be cost effective in achieving the abatement target.

Contents

1. INTRODUCTION

There has been considerable interest in the incentives created by environmental policy to induce technical change in general and the adoption of novel abatement technology in particular (see for a survey Jaffe et al., 2002). Examples include scrubbers to abate sulfur dioxide emissions from smokestacks, catalytic converters to reduce automobile emissions of nitrogen oxides, and alternative fuel additives to replace lead in gasoline. The example of scrubbers is an interesting one in that their development was spurred largely with a technology standard. Introduction of a sulfur dioxide cap-and-trade program in the US, considered a more cost-effective policy, led to significant reductions in sulfur dioxide emissions but with much less deployment of scrubbers than under the technology standard (Ellerman et al., 2000). The lesson appears to be that while new technology may be an important result of environmental policy, a cost effective policy may not necessarily lead to widespread adoption of particular technologies.

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On the other hand, there may be technology externalities that are not fully captured in private decisions. Knowledge spillovers and network externalities are prime examples. In such cases, technology policy aimed at the technology externalities can be used to induce widespread adoption of pollution abatement technology and in turn improve cost effectiveness of the pollution abatement. Furthermore, technology externalities may differ from sector to sector, possibly affecting the overall costs of environmental policy. If this is the case, differentiating environmental policy between sectors increases its cost effectiveness (Rosendahl, 2004; Otto et al., 2006). We take such differentiated environmental policy as our starting point and study cost effectiveness of combining this environmental policy with different technology policies with respect to adoption of CO_2 abatement technology and ultimately with respect to abatement of CO_2 emissions. Is technology policy necessary in the first place? If yes, is it cheaper to use technology adoption subsidies or R&D subsidies directed to the CO_2 abatement technology? Do we also induce its adoption if we try to correct for all market failures associated with technical change throughout the economy?

Previous investigations of this issue include the econometric analyses of Jaffe and Stavins (1995) and Hassett and Metcalf (1995), who compare energy taxes with adoption subsidies regarding adoption of CO_2-abatement technology. Using theoretical models, Milliman and Prince (1989, 1992) and Jung et al. (1996), among others, compare several environmental policy instruments regarding adoption of CO_2-abatement technology, although these studies do not include technology policy instruments in their comparisons. In a computable general equilibrium setting, Gerlagh and van der Zwaan (2006) compare various policy instruments regarding adoption of CO_2 capture and -storage as a CO_2 abatement technology, although their comparison is also limited to environmental policy instruments only. Popp (2004) and Kverndokk et al. (2004) do not study adoption (of non-CO_2 intensive technology) per se but rather how adoption influences the cost effectiveness of carbon taxes and R&D subsidies with respect to CO_2 emission reduction.[1]

We combine these various approaches and compare CO_2-trading schemes, adoption subsidies, and R&D subsidies with respect to adoption of CO_2 abatement technology and ultimately with respect to cost effective abatement of CO_2 emissions. For this purpose, we develop a dynamic computable general equilibrium (CGE) model, in which we specify CO_2 capture and storage (CCS) as a discrete CO_2 abatement technology. CCS refers broadly to processes that separate CO_2 from industrial- or energy sources and isolate it from the atmosphere (IPCC, 2005). Specific approaches include those that separate CO_2 from the fuel before it is combusted and other approaches that remove it from flue gases after combustion. Storage technology has focused on geological formations such as saline aquifers or oil- and gas fields where, if chosen carefully and monitored, the expectation is that the CO_2 would remain isolated from the atmosphere permanently. The net reduction of CO_2 emissions depends on, among others, the fraction of CO_2 captured, the extent of efficiency loss in energy conversion and leakage during transport and storage. Technologies currently envisioned for CCS are subject to economies of scale and thus

[1] We refer to Jaffe et al. (2002) for a survey of all previous studies and to Requate (2005) for a more recent survey of previous studies using theoretical models only.

energy- and economic models indicate that the major contribution of CCS to CO_2 mitigation is likely to come from adoption in the electricity sector that are currently large point sources for CO_2 emissions (IPCC, 2005). Our overall goal is to construct simulations that reveal cost-effective combinations of environmental, R&D, and technology adoption policies.

2. BASIC FEATURES OF THE MODEL

We build on a dynamic CGE model that explicitly captures links between CO_2 emissions associated with energy use, directed technical change and the economy. This model is formulated as a mixed-complementarity problem using the Mathematical Programming System for General Equilibrium Analysis (Rutherford, 1999). A full description of the model is provided in Otto et al. (2006). Here we restrict ourselves to a description of the basic features of the model and focus on the new specifications that relate to electricity generation technology that include CCS.

2.1. Model specifications

We specify a single representative consumer and representative producers in each of the following 7 aggregate sectors: (1) agriculture, (2) energy-intensive industry, (3) non-energy intensive industry and services, (4) trade and transport, (5) energy, (6) CO_2-intensive electricity and (7) non-CO_2 intensive electricity. The energy sector comprises the oil- and gas industries. Agents behave rationally and have perfect foresight. The representative consumer maximizes discounted welfare subject to the intertemporal budget constraint. Discounted welfare is a function of the discounted sum of consumption over the time horizon. The model is designed to examine cost-effectiveness of abatement options and environmental quality therefore does not enter the utility function, implying independence of the demand functions for goods with respect to environmental quality.

Producers maximize profits over time subject to their production-possibility frontier, which are determined by nested constant-elasticity-of-substitution functions of knowledge capital, physical capital, labor, and intermediate inputs. In addition, imported coal is used in the production of energy-intensive goods and CO_2-intensive electricity. Intermediate usage of oil, gas, and coal entail CO_2 emissions, which might be subject to quantity constraints, i.e. CO_2 trading schemes. To meet these constraints, several CO_2 abatement options are available to the producer. These options include, among others, a reduction in overall energy use, a shift away from fossil fuels as input, and technical change to increase efficiency of production or to develop CCS as a CO_2 abatement technology in the electricity sector. We specify gas-fired and coal-fired electricity generation technologies with CCS (henceforth referred to as gas or coal CCS technology) as a perfect substitute for those technologies without CCS in the CO_2-intensive electricity sector. The CCS technologies are characterized by separate constant-elasticity-of-substitution functions of knowledge capital, physical capital, labor, and intermediate inputs. We assume that engineers and scientists working in conventional power plants would also be involved in applying CCS technologies and the latter therefore use the same knowledge capital as the former. Fixed proportions between the various inputs ensure that the CCS technologies are specified as discrete technologies.

Technical change is characterized by innovation possibility frontiers, which describe investment in knowledge capital in the sectors. Knowledge capital is sector specific (c.f. Basu and Weil, 1998) and investments in knowledge capital merely involve final goods as input. In addition, there is a delayed technology externality in innovation in that previous investments in knowledge capital have a positive external effect on the efficiency of current investments. Knowledge spillovers and network effects, among others, underlie this technology externality, which also is sector specific because we assume that knowledge capital in one sector is too different to benefit from advances in other sectors. Finally, knowledge-capital investments accumulate into stocks, and we assume these give rise to an additional technology externality in sectoral production. While we only model explicitly one representative producer per sector, the technology externalities mean that the representative producer does not consider these externalities in making investment decisions and thus underinvests in knowledge capital from a social welfare perspective. The approach thus approximates the results of modeling a sector as composed of multiple individual firms, where a firm can capture some of the rents associated with its innovation but cannot capture the full returns to knowledge capital based on demand of the entire sector.

2.2. Equilibrium and growth

We solve the model so that each agent's decisions are consistent with welfare maximization in the case of the representative consumer and profit maximization in the case of producers. When income is balanced and markets clear at all points in time as well, the output, price and income paths constitute an equilibrium. Markets for production factors and final goods are perfectly competitive but there initially is no market for CO_2 emissions associated with energy use. The technology externalities support non-convexities in the possibility frontiers and cause private and social returns to knowledge capital to diverge. As a result, when these externalities are present the social welfare optimum diverges from the solution resulting from private agent's optimizing decisions.

Economic growth reflects the growth rates of the labor supply and stocks of physical and knowledge capital. Growth of the labor supply is exogenous and constant over time. Growth rates of both capital stocks stem from endogenous saving and investment behavior. The economy achieves balanced growth over time with the stocks of physical and knowledge capital growing at the same rate as the labor supply.

3. CALIBRATION

We calibrate our model to the Dutch economy in 1999. We consider a 32-year time horizon, defined over the years 1999 through 2030, and calibrate the model to a balanced growth path of two percent. We use central parameter values and data presented in Appendices A and B of Otto et al. (2006) and refer to this publication for more details about the calibration procedure. We restrict ourselves here to describing the calibration of the new feature of our model: the CCS technologies.

Electricity generation technologies fired by natural gas and coal are being used for respectively base- and mid-load electricity demand in the Netherlands. **Table 1** shows the expected costs of these electricity generation technologies with CCS in the Netherlands (see for a more detailed comparison of the various CCS technology options Damen et al., 2006).

The generation costs are based on natural-gas combined cycle (NGCC), pulverized-coal fired power plants (PC) and integrated coal gasification combined cycle (IGCC) and include cost estimates for CO_2 capture but not storage. Equipping the PC technology with CCS results in a slightly higher CO_2 capture rate than when the other electricity technologies are equipped with CCS. Regarding storage, we use a cost estimate of 5 €/t CO_2 stored, which includes pipeline transport to and injection in the gas fields in the North Sea or the north of the Netherlands. Further, transmission and distribution costs must be incorporated to make a clean comparison with the cost of conventional electricity in the model. Overall, the NGCC technology with CCS is 8% more expensive than the cost of conventional electricity whereas the IGCC and PC technologies with CCS are 17 and 25% more expensive. These estimates of cost ‘markup’ correspond with other studies (see e.g. McFarland et al., 2004). Yet, since the components of CCS are in various stages of development and none of these electricity generation technologies have yet been built on a full scale with CCS, ultimate costs of CCS cannot be stated with certainty. Neither do we know the full potential of CCS with precision. We assume that all CO_2 captured in the Netherlands can also be stored and focus on subsequent adoption of CCS. For simplicity, we assume adoption can be immediate. Nevertheless, it is expected that further technical change will bring down costs or increase potential or both over time.

Table 1. Cost of electricity with CO_2 capture and storage in the Netherlands (€ct/kWh).

		With CCS		
Electricity generation and CO_2 capture	**Without CCS**	**NGCC**	**IGCC**	**PC**
Capital		1.5	2.7	3.0
Fuel		3.0	1.5	1.6
Operation and maintenance		0.5	1.2	1.4
CO_2 storage		0.2	0.5	0.4
Transmission and distribution		2.9	2.9	2.9
Total	7.5	8.1	8.8	9.3
Markup (%)	0	8	17	24
CO_2 capture rate (%)	0	85	85	90

NGCC refers to natural gas combined cycle, IGCC refers to integrated coal gasification combined cycle and PC refers to pulverized coal. Fuel costs of natural gas are based on 4€/GJ and fuel costs of coal are based on 1.5 €/GJ. Storage costs are based on 5 €/t CO_2. We draw on Damen et al. (2006) for CCS-related data, IEA (1999) for transmission- and distribution cost shares and Eurostat for the cost of conventional electricity.

4. SIMULATIONS

We analyze the cost-effectiveness of environmental policy either alone or combined with technology policy to induce adoption of the gas CCS technology. The emissions target achieves a 40% reduction relative to the reference case, approximating stabilization of CO_2 emissions at 1990 levels for the Netherlands, as agreed upon in the Kyoto protocol. This assumes the 1990 level would also apply in post-Kyoto commitment periods (i.e. after 2012) to the end of the model horizon. Environmental policy takes the form of CO_2 trading schemes, which we differentiate between CO_2 intensive and non-CO_2 intensive sectors. We label agriculture, non-energy intensive industries and services, and non-CO_2 intensive electricity as non-CO_2 intensive sectors and energy-intensive industries, trade and transport, energy, and CO_2-intensive electricity as CO_2-intensive sectors. Technology policy is aimed at the internalization of positive technology externalities that may underlie non-adoption of the CCS technology and takes the form of technology adoption subsidies or R&D subsidies. We direct R&D subsidies only to the development of the CCS technology or generally to the development of technologies throughout the economy. In the last case, we differentiate the subsidies between CO_2 intensive- and non-CO_2 intensive sectors. In either case, we 'earmark' the R&D subsidy for the CCS technologies such that the use of knowledge capital by conventional technologies in the CO_2-intensive electricity sector is limited to the replacement of obsolete knowledge capital and all other knowledge capital is used by the CCS technologies. To avoid leakage of CO_2 emissions to consumption in all simulations, we also abate these emissions by 40% relative to the reference case using a separate quantity constraint.[2] We introduce the policies from 2007 onward and conduct a gridded search across the parameter space of the policies to find the cost effective policy combinations. We explore the potential of coal CCS technologies in the sensitivity analysis. **Table 2** summarizes the four simulations.

Table 2. Effects of policies on discounted welfare and adoption of CCS technology.

Simulation	**Discounted welfare** (%)	**Year of adoption**
Reference	0.00	No
1 Differentiated CO_2-trading schemes	–1.46	2023
2 Combination of differentiated CO_2-trading schemes and an adoption subsidy	–0.75	2007
3 Combination of differentiated CO_2-trading schemes and a directed R&D subsidy	–1.19	2009
4 Combination of differentiated CO_2-trading schemes and differentiated R&D subsidies	13.84	2009

Discounted welfare is expressed in percentage changes relative to the reference case.

4.1. Simulation 1: Differentiated CO_2-trading schemes

Figure 1 shows effects of the cost-effective set of differentiated CO_2-trading schemes on electricity generation. The trading schemes yield a discounted welfare loss of 1.45% and entail shadow prices of €11.55 and €1.00 per ton CO_2 in respectively the CO_2 intensive- and non-CO_2 intensive sectors. By pricing CO_2 emissions, the trading schemes improve the competitiveness of the CCS technology and induce its adoption, albeit only from 2023 onward. In the meantime, CO_2 efficiency of the conventional electricity generation technologies improves instead, making it more difficult for the CCS technology to enter. Once the CCS technology has been adopted, however, large quantities of electricity can then be generated in a non-CO_2 intensive manner. As a result, electricity itself then gains market share as an energy carrier, which further increases output of the CCS technology.

[2] Note that CO_2 emissions abroad can increase as we only investigate domestic abatement. Yet, we use an Armington specification that closes international trade in a way that limits this leakage effect.

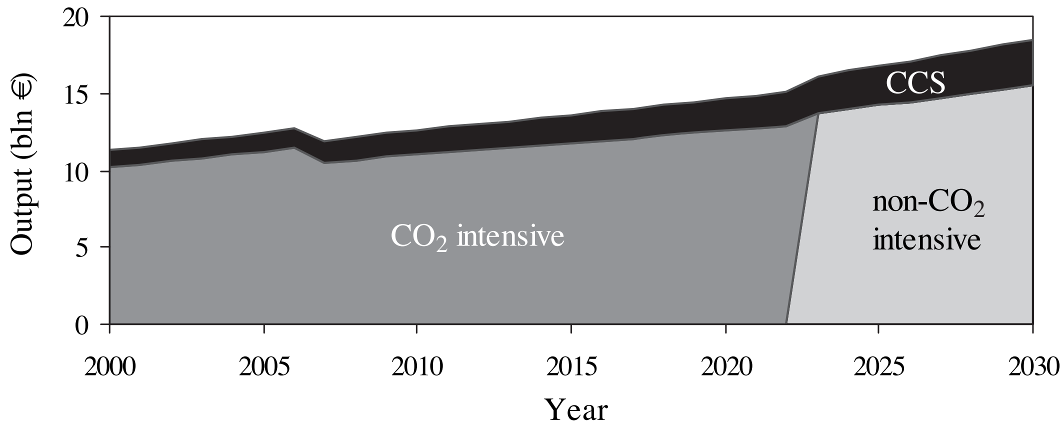

Figure 1. Effects of the cost-effective set of differentiated CO_2-trading schemes on electricity generation per technology (bln. €).

4.2. Simulation 2: Combination of differentiated CO_2-trading schemes and an adoption subsidy

Figure 2 shows that the cost-effective combination of differentiated CO_2-trading schemes with an adoption subsidy for CCS technology is very effective in inducing its adoption. By directly compensating for the markup over the cost of conventional electricity, the CCS technology becomes competitive from the moment the adoption subsidy is introduced and immediately substitutes for the conventional technologies used in the CO_2-intensive electricity sector. This result is in line with empirical findings by Jaffe and Stavins (1995) and Hassett and Metcalf (1995) that show technology adoption subsidies to be more effective in inducing adoption of energy conservation technologies than energy taxes.

The cost-effective combination of instruments comprises shadow prices of €6.65 and €4.95 per ton CO_2 in the CO_2 intensive- and non-CO_2 intensive sectors and an adoption subsidy of 21% and entails a discounted welfare loss of 0.75%. This loss is lower than in the first simulation with just the CO_2 trading schemes because the adoption subsidy corrects for positive technology externalities related to the CCS technology (see Table 2). Technology externalities lead to underinvestment in the CCS technology according to what is optimal from a social welfare

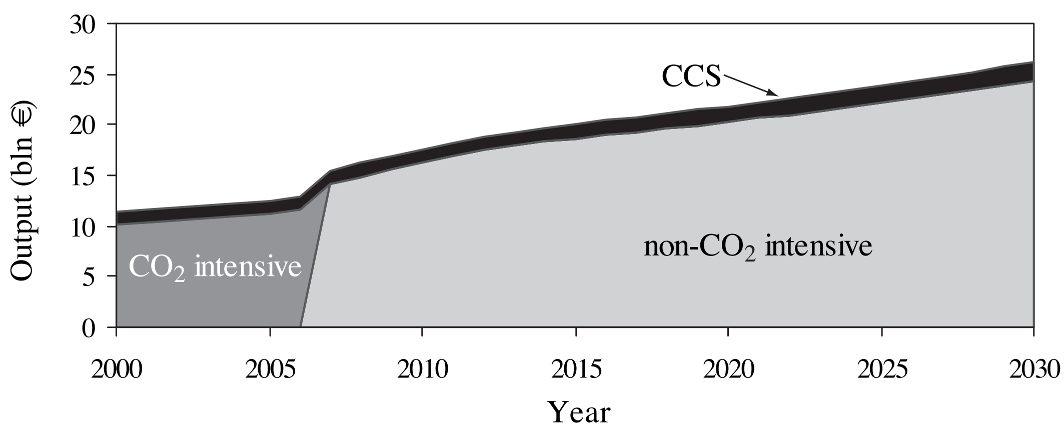

Figure 2. Effects of the cost-effective combination of differentiated CO_2-trading schemes and an adoption subsidy on electricity generation per technology (bln. €).

perspective. Knowledge gained during the development phase of the CCS technology, for example, might spill over to other firms in the electricity- or energy sector and indirectly increase their productivity. By subsidizing the use of the CCS technology, we 'pull' this technology out of its development phase and consequently bring its investment levels closer to the socially optimal level.

4.3. Simulation 3: Combination of differentiated CO_2-trading schemes and a directed R&D subsidy

Figure 3 shows that the cost-effective combination of differentiated CO_2-trading schemes with an R&D subsidy directed to CCS technology also induces its adoption, albeit later in time and at a slower rate than with the adoption subsidy. Whereas the adoption subsidy directly improves competitiveness of the CCS technology by lowering its output price, the directed R&D subsidy only indirectly improves competitiveness by lowering one of the various input prices. It is only when sufficient knowledge capital has been accumulated that the input costs of knowledge capital services decreases to the extent that the CCS technology becomes competitive and gains market share. Similar to the first simulation with only the trading schemes, CO_2 efficiency of conventional electricity generation technologies improves in the meantime, making it more difficult for the CCS technology to gain market share.

The cost-effective combination of instruments now comprises shadow prices of €10.50 and €1.05 per ton CO_2 in the CO_2 intensive- and non-CO_2 intensive sectors and a directed R&D subsidy of 59% and entails a discounted welfare loss of 1.19%. This loss is lower than in the first simulation with only the trading schemes, but higher than in the second simulation with the additional adoption subsidy (see Table 2). Although the directed R&D subsidy also corrects for technology externalities associated with the CCS technology, it takes more time to receive the returns on the investments than with the adoption subsidy.

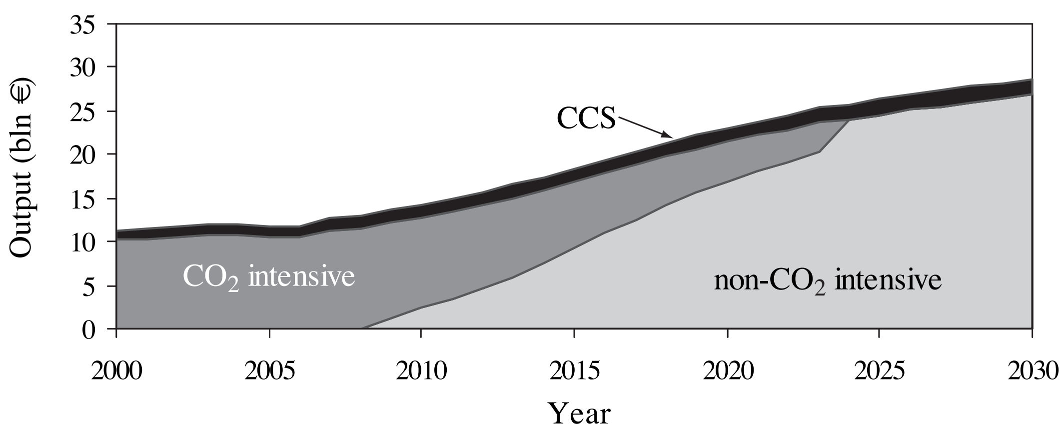

Figure 3. Effects of the cost-effective combination of differentiated CO_2-trading schemes and a directed R&D subsidy on electricity generation per technology (bln. €).

4.4. Simulation 4: Combination of differentiated CO_2-trading schemes and differentiated R&D subsidies

Figure 4 shows that the cost-effective combination of differentiated CO_2-trading schemes with differentiated R&D subsidies throughout the economy leads to more and faster adoption of

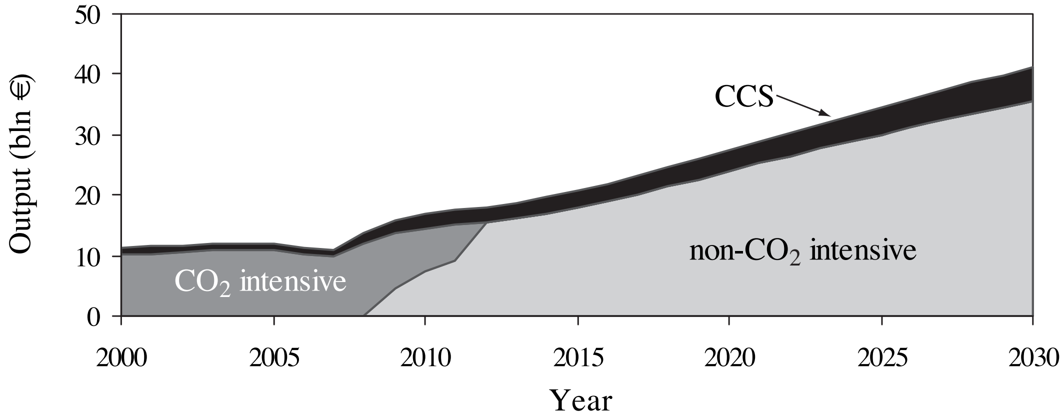

Figure 4. Effects of the cost-effective combination of differentiated CO_2-trading schemes and differentiated R&D subsidies on electricity generation per technology (bln. €).

CCS technology than in the previous simulation with the R&D subsidy directed only to the CCS technology. More specifically, the cost-effective combination of instruments now comprises shadow prices of €19.60 and €10.10 per ton CO_2 in the CO_2 intensive- and non-CO_2 intensive sectors as well as R&D subsidies of 60% and 51% in the respective sectors. In contrast to the R&D subsidy directed only to CCS technology, the optimal set of differentiated R&D subsidies enhances economic growth in the whole economy and further increases the shadow prices of CO_2. Both these effects improve the competitiveness of CCS technology. Compared to the second simulation with the adoption subsidy, however, adoption occurs later in time and remains slower. Whereas R&D subsidies are first-best instruments to internalize technology externalities, they are not necessarily the most effective instruments to induce adoption of new technology because they only indirectly improve competitiveness of new technology as discussed above. Nevertheless, discounted welfare increases by 13.84% relative to the reference case and this policy combination is therefore superior from a welfare perspective as technology externalities are internalized throughout the whole economy.

4.5. Effects on CO_2 emissions

Figure 5 shows effects of the cost-effective policies identified in the four simulations above on CO_2 emissions in the Dutch economy. Aggregate CO_2 emissions are abated by 40% relative to the reference case, which corresponds to stabilization of emissions around 160 Mt CO_2 per year. The typical abatement pattern consists of relatively less abatement in early years and more abatement in later years. In the fourth simulation with both the trading schemes and the optimally differentiated R&D subsidies, for example, emissions are abated by a mere 15-20% in the first couple of years after the policies have been introduced whereas emissions are abated by about 50% toward the end of the time horizon. Both the technology externalities and the adoption of CCS technology in later years reduce abatement costs in the future and hence reduce shadow prices of CO_2 emissions today (Goulder and Mathai, 2000). In the second simulation with the adoption subsidy, however, abatement is spread more evenly over time as the CCS technology is adopted immediately after the policies are introduced.

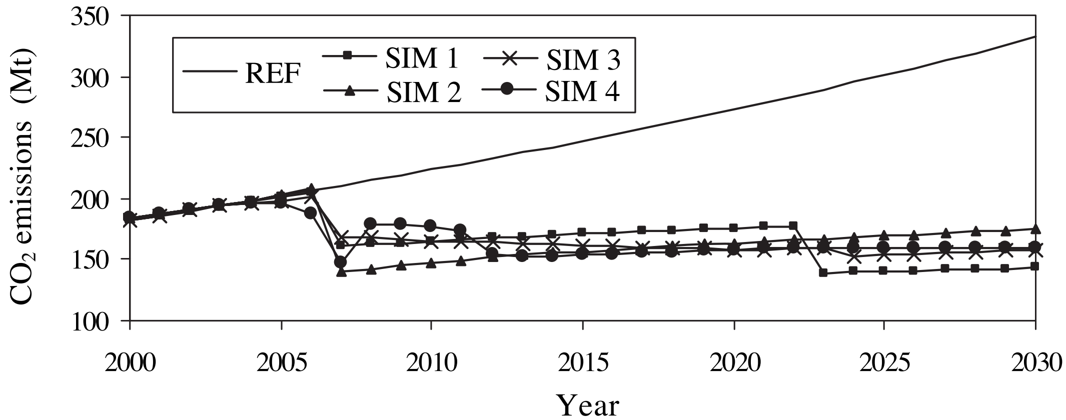

Figure 5. Effects of the policy combinations on aggregate CO_2 emissions (Mt CO_2).

Sectoral emission patterns also exhibit variation across the simulations. CO_2 intensities, differentiation of the policy instruments and adoption of the CCS technology all determine which sectors abate more and which sectors abate less. **Figures 6** and **7** show effects of the cost-effective policies identified in the simulations above on CO_2 emissions in the two sectors most affected by possible adoption of CCS technology: the CO_2-intensive electricity sector and the energy sector.

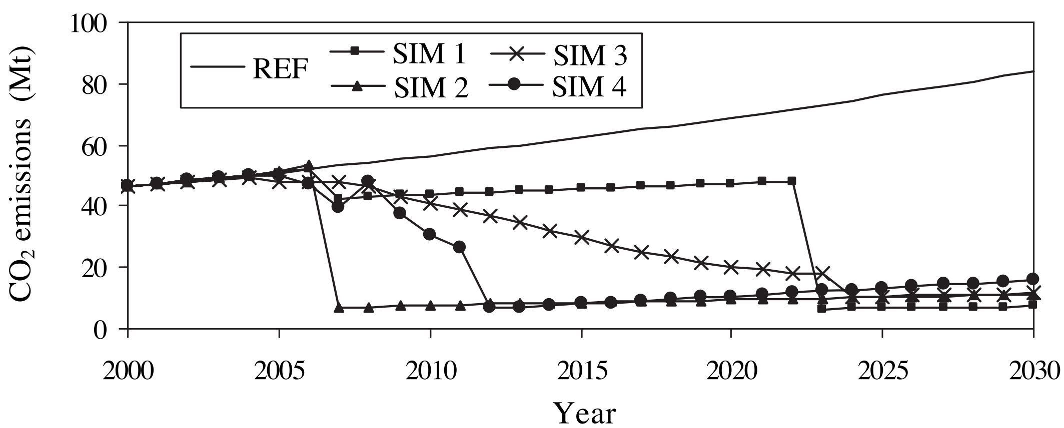

Figure 6. Effects of the policy combinations on CO_2 emissions in the electricity sectors (Mt CO_2)

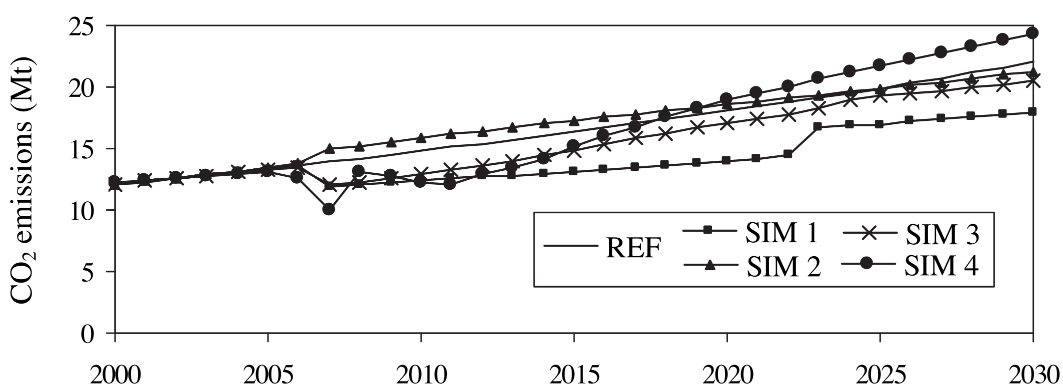

Figure 7. Effects of the policy combinations on CO_2 emissions in the energy sector (Mt CO_2).

Regarding the CO_2-intensive electricity sector, CO_2 emission levels correspond to the amount of electricity generated with the various generation technologies as shown in Figures 1 through 4. The CCS technology is adopted to varying extents in the four simulations and the abatement burden of the CO_2-intensive electricity sector consequently increases to these extents.

Regarding the energy sector, abatement of its CO_2 emissions correspond *inversely* to abatement of emissions in the CO_2-intensive electricity sector. The more the CCS technology is adopted in the CO_2-intensive electricity sector, the more market share electricity gains as an energy carrier and the more natural gas is demanded by the electricity sector ultimately leading to more CO_2 emissions in the energy sector. This effect is especially visible in the last three simulations with the additional technology policies and highlights that technology policy does not necessarily provide incentives to reduce energy use.

4.6. Fiscal implications

The cost-effective policies identified above have different fiscal implications (see **Table 3**). In the first simulation with only the CO_2 trading schemes, revenues from these schemes amount to 96 billion euros or 2.8% of gross domestic output over the entire 24-year period the trading schemes are in place.

These revenues are sufficient to finance technology policy that is limited in scope. Indeed, expenditures on the adoption subsidy amount to 32 billion euros or 0.9% of gross domestic output while revenues from the trading schemes are 83 billion euros or 2.4% of gross domestic output in the second simulation. Compared to the first simulation with only the trading schemes, however, revenues from these trading schemes now fall by 13 billion euros as the immediate adoption of the CCS technology makes it cost effective to shift some of the abatement burden away from the CO_2-intensive sectors. Similar fiscal implications can be observed in the third simulation with the R&D subsidy for CCS instead of the adoption subsidy. As it is cost effective to let the CCS technology gain market share only gradually in this simulation, both the R&D subsidy for CCS and its fiscal implications are smaller in size.

Finally, the fourth simulation with the optimally differentiated R&D subsidies shows clearly that there is a limit to the extent that revenues from the trading schemes can be used to finance technology policy. The expenditures on the R&D subsidies are now a factor of 10 larger than the

Table 3. Fiscal implications of the policies.

Simulation:	1	2	3	4
Gross domestic output in billion euros	3,425	3,482	3,446	5,493
Revenues from the CO_2 trading schemes In billion euros	96	83	91	158
As share of gross domestic output (%)	2.8	2.4	2.7	2.9
Expenditures on the subsidies In billion euros		32	12	1,536
As share of gross domestic output (%)		0.9	0.4	28.0

Numbers are aggregated from the time the policies are introduced (2007) till the end of the time period under study (2030) and are expressed as present values. Simulation 1 refers to differentiated CO_2-trading schemes; simulation 2 to the combination of differentiated CO_2-trading schemes and an adoption subsidy; simulation 3 to the combination of differentiated CO_2-trading schemes and a directed R&D subsidy; and simulation 4 to the combination of differentiated CO_2-trading schemes and differentiated R&D subsidies. Policies reported for these simulations are the cost effective policies to achieve the emission reduction and are not necessarily the minimum policies required to induce adoption of the CCS technology.

revenues from the trading schemes. Yet, this simulation also shows clearly that technology policy pays for itself in the sense that gross domestic output increases more than the expenditures on the R&D subsidies. The latter now amounts to 1,536 billion euros over the entire 24-year period the policies are in place whereas the former increases from 3,425 to 5,493 billion euros.

4.7. Sensitivity analysis

Table 4 reports the sensitivity of our results to key parameter values. We use central parameter values in all sensitivity simulations except for the parameter subject to analysis. We limit ourselves to CCS-related parameters given our focus on technology adoption.

We find that our results are robust to the range of parameter values considered. Combining differentiated CO_2-trading schemes with the adoption subsidy remains the most effective set of policy instruments to induce CCS technology whereas combining the CO_2-trading schemes with the optimal set of differentiated R&D subsidies remains the cost-effective set of policy instruments to induce CCS technology and ultimately to achieve the abatement target.

Turning to the specific parameters subject to analysis, increasing the coefficient value of technology externalities associated with innovation of the CCS technology by 25% has a positive effect on discounted welfare and adoption of the of the CCS technology as its productivity improves faster. This is especially visible in simulations 3 and 4, in which adoption occurs not immediately after the introduction of the policy combination. Further, halving the storage costs of the CCS technology to €2.50 per ton CO_2 has a positive effect on discounted welfare and adoption of the CCS technology as well because the lower storage costs reduce the markup over the cost of conventional electricity. The opposite applies if we double the storage costs to €10 per ton CO_2. Finally, specifying CCS also for PC and IGCC does not lead to any adoption of these technologies because of their high markup relative to the CCS technology for NGCC. Consequently, discounted welfare and adoption of the gas CCS technology are not affected.

Table 4. Piecemeal sensitivity analysis.

Discounted welfare (% change) **Simulation**:	**1**	**2**	**3**	**4**
Regular simulation	0.00	0.00	0.00	0.00
25% higher externalities for CCS	0.00	0.02	0.05	0.01
Storage costs halved	0.07	0.05	0.09	0.03
Storage costs doubled	–0.16	–0.10	–0.23	–0.07
CCS for coal-fired plants	0.00	0.00	0.00	0.00
Cumulative output-share of CCS for gas-fired plants (%)	**1**	**2**	**3**	**4**
Regular simulation	38.4	100	72.6	91.9
25% higher externalities for CCS	38.4	100	74.2	92.4
Storage costs halved	43.0	100	75.6	93.7
Storage costs doubled	24.3	100	67.8	87.6
CCS for coal-fired plants	38.4	100	72.6	91.9

Numbers are cumulative output shares of the CCS for gas-fired power plants in the CO_2-intensive electricity sector. Simulation 1 refers to differentiated CO_2-trading schemes; simulation 2 to the combination of differentiated CO_2-trading schemes and an adoption subsidy; simulation 3 to the combination of differentiated CO_2-trading schemes and a directed R&D subsidy; and simulation 4 to the combination of differentiated CO_2-trading schemes and differentiated R&D subsidies. Neither the CCS for pulverized-coal fired plants nor the CCS for integrated coal gasification combined cycles are adopted and hence their market shares are not reported.

5. CONCLUSIONS

Environmental policy, such as trading schemes to abate CO_2 emissions, can induce technical change. Although novel abatement technology may be an important result of environmental policy, a cost effective policy may not necessarily lead to widespread adoption of such technology because of prohibitive costs or technology externalities, or both. Technology policy aimed at the technology externalities can be used to induce more widespread adoption of CO_2 abatement technology and in turn improve cost effectiveness of the abatement. In addition, differentiating policy between sectors may further increase its cost effectiveness if technology externalities differ from sector to sector. As a caveat, we did not study institutional aspects of technology policy or the precise form such policy should take in practice. Instead, we addressed more general questions first: Is technology policy necessary in the first place? If yes, is it cheaper to use technology adoption subsidies or R&D subsidies directed to the CO_2 abatement technology? Do we also induce its adoption if we try to correct for all market failures associated with technical change throughout the economy?

To answer these questions, we developed a dynamic CGE model, in which we specified CCS as a CO_2 abatement technology for gas-fired power plants in the CO_2-intensive electricity sector. Simulations revealed which policy combination is cost effective with respect to adoption of the CCS technology and ultimately with respect to abatement of CO_2 emissions.

Although it takes time, CO_2-trading schemes alone are sufficient to induce adoption of the CCS technology under current abatement targets. Combining the CO_2-trading schemes with R&D subsidies that are optimally differentiated across CO_2-intensive- and non-CO_2 intensive sectors leads to faster adoption of the CCS technology and is cost effective in achieving the abatement target. In fact, the economy improves relative to the reference case because of the correction for technology externalities throughout the whole economy. Although R&D subsidies are the first-best instrument to internalize technology externalities, they are not necessarily the most effective instrument to induce adoption of new technology. For that purpose, an adoption subsidy is preferred. Such a subsidy directly improves the competitiveness of the CCS technology by compensating for its markup over the cost of conventional electricity. Consequently, the CCS technology immediately substitutes for the conventional technologies used in the CO_2-intensive electricity sector.

Policy combinations that involve CO_2-trading schemes, R&D, and adoption subsidies thus are more cost-effective in achieving the abatement target. Yet, the difficulty remains how to get this policy choice right in reality. In a model, we can search for the best combination but our ability to accurately characterize the real possibility frontier for a technology like CCS is necessarily limited. How inexpensive can engineers make it and how much effort will that take? How much of any gain from such R&D will be appropriated and how much will spill over? Clear empirical answers to those questions are needed to guide the optimal choice of policy. Our research supports the idea that all policy combinations under study can play a role, but any policy needs to be carefully formulated and evaluated in terms of whether it is actually achieving the goal, or whether it has ceased to be needed because, for example, knowledge spillovers have been widely exhausted.

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