Directed Technical Change and Climate Policy

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Summary

This paper studies the cost effectiveness of climate policy if there are technology externalities. For this purpose, we develop a forward-looking CGE model that captures empirical links between CO2 emissions associated with energy use, directed technical change and the economy. We find the cost-effective climate policy to include a combination of R&D subsidies and CO2 emission constraints, although R&D subsidies raise the shadow value of the CO2 constraint (*i.e.* CO2 price) because of a strong rebound effect from stimulating innovation. Furthermore, we find that CO2 constraints differentiated toward CO2-intensive sectors are more cost effective than constraints that generate uniform CO2 prices among sectors. Differentiated CO2 prices, through technical change and concomitant technology externalities, encourage growth in the non-CO2 intensive sectors and discourage growth in CO2-intensive sectors. Thus, it is cost effective to let the latter bear relatively more of the abatement burden. This result is robust to whether emission constraints, R&D subsidies or combinations of both are used to reduce CO2 emissions.

Keywords: Directed Technical Change, Climate Policy, Computable General Equilibrium Model, R&D

JEL Classification: D58, H21, H23, O33, O38

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1. Introduction

There is an increasing consensus that growing emissions of greenhouse gases pose a serious threat to the world. One strategy for addressing this threat is to use environmental policy such as a cap and trade system to constrain emissions; the approach envisioned in the Kyoto Protocol of the Framework Convention on Climate Change that has entered into force and will be implemented in most industrial nations beginning in 2008. The use of a cap and trade system in this agreement was seen as a success of economic reasoning by many, because such systems are widely heralded as generating a given level of abatement in the most "cost-effective" manner. The Bush Administration has taken the United States out of the Kyoto Protocol and instead adopted a technology policy that includes support for R&D as an alternative strategy, with the idea that without technological options to reduce greenhouse gases an emission constraint will mostly punish the economy by slowing economic growth. While such a punishment seems mostly exaggerated for "small" reductions in emissions the ultimate goal of the Framework Convention, stabilization of greenhouse gas concentrations, requires that the world economy reduces emissions by 90 to 95% from best projections of where it otherwise would be. This is untested territory, and thus the need for new technology is real if these stabilization goals are to be met. However, even recognizing that new technology is needed, one might believe that appropriate environmental policy instruments—the right emissions constraint or tax—would induce new technologies.

We study the cost effectiveness of these different strategies. If emissions are priced will that induce technical change? Can R&D subsidies achieve emission reductions, and is this strategy cheaper than using emission constraints? Are the two strategies complementary? Can one improve on uniform emission-reduction policy by differentiating policy toward relatively dirty technologies? Previous investigations of the two strategies include Jaffe *et al.* (2005) and the general equilibrium analyses of Goulder and Schneider (1999) and Popp (2004), who show that carbon taxes are cost effective when they are complemented by a R&D subsidy. In a cost-minimization setting, Rosendahl (2004) and Bramoullé and Olson (2005) demonstrate theoretically that technology externalities call for differentiation of pollution taxes. We proceed by empirically studying these different strategies in which we pay specific attention to their differentiation.

For this purpose, we develop a forward-looking computable general equilibrium (CGE) model that captures empirical links between CO_2 emissions associated with energy use, directed technical change and the economy. We draw on endogenous growth models of Rivera-Batiz and Romer (1991) and Acemoglu (2002) and specify technologies as stocks of knowledge capital that are sector-specific investment goods, which have associated positive externalities. We calibrate the model to the Dutch economy, where availability of investment data for knowledge capital that is consistent with the national accounting framework allows us to pay special attention to its representation in the benchmark data. Simulations are constructed to reveal cost effective combinations of CO_2 constraints and R&D subsidies, including the desirability of differentiating these instruments among clean and dirty sectors.

2. Basic features of the model

This section describes the key specifications of our model. We offer a full description of the model in Appendix A.

Model specifications

We specify a representative consumer and producers in the following sectors: agriculture (AGR), CO_2-intensive industry (IND), non-CO_2 intensive industry and services (SER), trade and transport (TT), energy (NRG), CO_2-intensive electricity (CIE) and non-CO_2 intensive electricity (NCIE), where the energy sector comprises the oil- and gas industries. Agents behave rationally and have perfect foresight. A representative consumer maximizes intertemporal utility subject to the intertemporal budget constraint. Intertemporal utility is a function of the discounted sum of consumption over the time horizon. Environmental quality 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 (CES) functions of knowledge capital, physical capital, labor, and intermediate inputs. In addition, imported coal is used in the production of CO_2-intensive goods and electricity. Intermediate usage of oil, gas, and coal entail CO_2 emissions, which might be subject to quantity constraints, *i.e.* cap and trade systems.

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). Further, technical change is a deterministic process and aggregate innovation possibility frontiers are continuous, which allows us to avoid problems due to uncertainty or integer variables.[1] Investments in knowledge capital merely involve final goods as input. In addition, there is positive delayed feedback in technical change in that previous investments in

[1] Even though indivisibility of knowledge capital and uncertainty related to R&D processes are facts of life, averaging out makes these facts matter less at aggregate levels (Romer, 1990).

knowledge capital have a positive external effect on the efficiency of current investments, *i.e.* learning-by-researching (henceforth referred to as positive feedback).[2] We specify this positive feedback operating within each sector only but relax this assumption in the sensitivity analysis. Finally, knowledge-capital investments accumulate into stocks, which gives rise to an additional technology externality on sector production. The rationale for this externality is that, while producers can prevent others from using their knowledge capital by means of patent protection, they cannot completely prevent knowledge embodied in patents from spilling over to other producers in their sector. These two types of technology externalities lead to the result that profit maximizing firms underinvest in R&D and thus there exists a rationale to subsidize investments in knowledge capital (henceforth referred to as R&D subsidies).

Regarding international trade, domestically produced goods and physical capital are allocated between domestic and export markets. Goods traded on domestic markets are combined with imported goods into an Armington (1969) aggregate, which satisfies demand for intermediate- and final goods. An exception is coal imports, which are directly used in certain CO_2-intensive industries and the CO_2-intensive electricity sector. Domestic investment in physical capital is combined with foreign investment into an Armington aggregate as well, satisfying investment demand for physical capital. We do not model international trade in knowledge capital. As a small open economy, it is potentially easy for the Netherlands to meet CO_2-emission constraints by specializing in non-CO_2 intensive sectors so that the implied emissions occur outside the economy. While that might be a realistic response for a small economy independently pursuing a CO_2 reduction policy, if it succeeds only by increasing emissions elsewhere there is little or no real climate benefit. The Armington specification, as opposed to a Heckscher-Ohlin formulation, closes international trade in a way that limits this leakage effect.

Equilibrium and growth

Each agent solves its optimization problem. When markets clear at all points in time, 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 nonconvexities in the possibility frontiers and cause private and social returns to knowledge capital to diverge.

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

[2] Rivera-Batiz and Romer (1991) dub this specification ‘knowledge-based’ in contrast to the former specification, which they dub ‘lab-equipment’ for its emphasis on physical inputs.

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

In this section, we describe the calibration of our model in which we pay special attention to the accounting of knowledge capital. Accounting for knowledge capital in CGE models is relatively new and, when undertaken, is typically done in a rudimentary fashion because of absence of detailed information. Because of the availability of investment data for knowledge capital in The Netherlands that is consistent with the national accounting framework, we calibrate our model to the Dutch economy. We choose 1999 as the benchmark year.

Accounting for knowledge capital

To account for knowledge capital, we identify and capitalize flows associated with knowledge and subsequently incorporate these in the national accounting matrix (Statistics Netherlands, 2000). We follow De Haan and Rooijen-Horsten (2004) and identify expenditures on R&D, expenditures on education (EDU) and investments in information- and communication infrastructure (ICT) as knowledge flows.[3] ICT is included because of its role in disseminating and storing knowledge and is therefore an important part of the infrastructure required for knowledge capital to be productive.

To capitalize these knowledge flows, we take the following two steps. First, we create an additional (column) account registering investments in the stock of knowledge capital and an additional (row) account registering services derived from the stock. Investment in ICT is reported as investment and expenditures on R&D and education are reported as derived services. We assume the Dutch economy to be on a balanced growth path in 1999, which implies a fixed relation between investments in and services derived from the sector-specific stocks of knowledge capital. This relation gives us the total column and row accounts for knowledge capital as a result of the three knowledge flows. Second, we debit the national accounting matrix to avoid double counting. Given that investments in ICT are originally reported as investments in

[3] We are aware that this identification entails to a certain degree unavoidable randomness. There are many types of knowledge and knowledge may be embedded not only in software and books but also in *e.g.* people and traditions. It therefore is difficult to comprehensively measure and aggregate knowledge. Yet, it is not altogether different from aggregating physical capital goods. The main difference is, of course, that it is difficult to attach a value to knowledge capital (Griliches, 1979).

physical capital, we debit the investment (column) account with the amounts of investment in ICT. Expenditures on R&D and education are originally reported as intermediate consumption requiring us to debit the intermediate goods matrix. We follow Terleckyj (1974) and assume that knowledge is embodied in tangible goods and services, which allows us to debit each sector's expenditures on education and R&D from the sector's consumption of intermediate goods proportionally to its sector of origin. We balance the national accounting matrix by adjusting the (row) account for labor.

Data and parameter values

Besides accounting for knowledge capital, we make further data adjustments to account for CO_2 emissions associated with energy use. We divide the electricity sector into CO_2-intensive and non-CO_2-intensive electricity generation using techno-economic data for the key technologies that are sufficient to give an appropriate representation for both types of electricity generation (Böhringer, *et al.*, 2003). Table B.1 presents cost structures and market shares of the electricity generation technologies in The Netherlands. Further, we obtain data on fossil-fuel inputs in The Netherlands from the GTAP-EG database (Paltsev and Rutherford, 2000) and match this data with CO_2 emission data for The Netherlands (Koch, *et al.*, 2002). We classify CO_2-intensive industry, trade and transport, energy and CO_2-intensive electricity as CO_2-intensive sectors and agriculture, non-CO_2 intensive industry and services and non-CO_2 intensive electricity as non-CO_2 intensive sectors. Table B.2 presents the national accounting matrix and Table B.3 reports factor- and CO_2 intensities.

Turning to model parameters, we use general parameter values that are standard in the literature (see Tables A5-6). Regarding international trade, however, we assume unitary substitution elasticity between domestic and foreign commodities, which is lower than is often used. This limits the leakage effect discussed above. Many of the largest trading partners of The Netherlands are implementing similar environmental policies, such as the EU emissions trading scheme, which limits effects of international trade on relative factor shares. Regarding technology-related parameters, we use a 25 percent depreciation rate for knowledge capital.[4] Pakes and Schankerman (1979) study patent renewals in the United Kingdom, Germany, France, The Netherlands and Switzerland and find a point estimate for the depreciation rate of 25 percent with a confidence interval between 18 and 35 percent. This estimate is consistent with data on

[4] Alternatively, one can take the view that knowledge doesn't depreciate at all. This assumption is likely to be valid if the sector or industry under study is narrowly defined and its stock of knowledge capital changes only slowly (Griliches, 1988). This assumption is less likely to be valid, however, if one defines sectors more broadly or for periods where one might suspect more rapid obsolescence of knowledge capital such as the decades following the ICT boom.

lifespans of applied R&D expenditures, which suggests an average service life of four to five years. More recently, Jorgenson and Stiroh (2000) have estimated a geometric depreciation rate for computer equipment and software of 31.5 percent. Further, we assume a positive feedback effect in technical change of 20 percent being the difference between the private- and social returns to knowledge capital. The former is at least equal to the 25-percent depreciation rate whereas estimates of the latter lie in the range of 30-60 percent (see *e.g.* Baumol, 2002, or Otto *et al.,* 2006, who find a positive feedback effect of 45 percent with delays up till eight years). We base the coefficient value for the knowledge spillovers on Coe and Helpman (1995) who estimate the elasticity of R&D stocks on total factor productivity at 9 percent for non-G7 OECD countries.

Finally, we consider a 27-year time horizon, defined over the years 1999 through 2025, and calibrate the model to a balanced growth path of two percent, which serves as reference case in the simulations below.

4. Simulations

We analyze cost-effectiveness of both environmental- and technology policy to reduce cumulative CO_2 emissions in production over the time horizon of the model by 10 percent relative to the reference case, where we differentiate both policies between CO_2-intensive and non-CO_2-intensive sectors. Environmental policy takes the form of quantity constraints for CO_2 emissions (*i.e.* cap and trade systems) and technology policy takes the form of R&D subsidies. To avoid leakage of CO_2 emissions to consumption in all simulations, we also reduce these emissions by 10 percent relative to the reference case using a separate quantity constraint.

Simulation 1: Differentiated CO_2-emission constraints

Figure 1 shows effects of the various possibilities to differentiate the CO_2 emission constraint between CO_2-intensive and non-CO_2-intensive sectors on shadow prices of CO_2 emissions in the sectors (lower graph) and discounted utility (upper graph). We explain this figure in several steps, starting with the horizontal axes that list percentage changes in CO_2 emissions of the non-CO_2-intensive sectors. As a first step, we set these percentage changes exogenously and calculate the CO_2-emission constraint for the CO_2-intensive sectors necessary for total emissions in production to be reduced by 10 percent. Second, we use the model to calculate the general equilibrium result associated with each differentiation of both CO_2 emission constraints. The lower graph maps the corresponding sets of shadow prices for CO_2 emissions required to meet the sectoral emission constraints. In general, technology externalities positively affect the shadow prices. In this simulation, however, we find the shadow prices with technology externalities to exhibit negligible differences from those without technology externalities.[5] For this reason, we present only one curve for each sector in this graph. Yet, the technology externalities have a noticeable effect on welfare. As a last step, therefore, we map the changes to discounted utility that correspond with each differentiation of the CO_2 emission constraints in the upper graph. Utility indices smaller than one imply welfare losses relative to the reference case. The upper curve shows the welfare loss if there are technology externalities whereas the lower curve shows the welfare loss if there are none. The left dashed vertical line represents the set of uniform shadow prices, which is the cost-effective (highest welfare) set if there are no technology externalities. The right dashed vertical line represents the set of differentiated shadow prices, which is the cost-effective set if there are technology externalities.

Insert Figure 1 here

We find that the conventional result of uniform shadow prices across sectors being cost effective holds if there are no technology externalities. The 10 percent emission reduction in production entails a welfare loss of 0.30 percent over the time period and results in a shadow price of €2.70 per ton CO_2 in all sectors. When there are technology externalities, however, we find that welfare is higher for all differentiations of the CO_2 emission constraints. If the constraints can be set at different levels, we find it cost effective to differentiate the constraints toward the CO_2-intensive sectors. The 10 percent emission reduction in production now entails a welfare loss of 0.28 percent over the time period and results in shadow prices of €2.80 per ton CO_2 in the CO_2-intensive sectors and €0.10 per ton CO_2 in the non-CO_2-intensive sectors. CO_2 emission constraints direct technical change toward non-CO_2 intensive sectors yielding relatively more technology externalities in these sectors and therefore raising their opportunity cost of abatement. The electricity sector, for example, redirects its R&D toward biomass and wind technologies resulting in relatively more knowledge spilling over from the development of these technologies than fossil-fuel electricity technologies. Thus, it is cheaper to shift some abatement toward CO_2-intensive technologies and sectors.

The bias in technical change can be best understood with help of the general framework presented by Acemoglu (2002) or the framework applied to energy biased technical change of

[5] The difference between shadow prices with and without technology externalities is difficult to graphically detect in this simulation. Technology externalities have a positive effect on the shadow price of CO_2 emissions because of their positive effect on welfare and hence overall demand for energy and concomitant CO_2 emissions. Yet, this effect is limited in this simulation because of the deadweight losses associated to the CO_2 emission constraints.

Otto *et al.* (2005). On the supply side of the economy, CO_2-emission constraints give rise to a substitution effect in production in that knowledge capital substitutes for fossil fuels raising the profitability of investing in knowledge capital in the CO_2-intensive sectors. On the demand side, however, CO_2-emission constraints give rise to a substitution effect in consumption as consumers shift toward non-CO_2-intensive goods raising the profitability of investing in knowledge capital in the non-CO_2-intensive sectors. When introducing CO_2 emission constraints, we find the demand side to be relatively important as substitution in consumption is necessary for cost-effective emission reduction. Technology externalities reinforce the bias.

Simulation 2: Differentiated R&D subsidies

We now study R&D subsidies as our instrument to reduce overall CO_2 emissions in production by 10 percent relative to the reference case. Figure 2 shows effects of the various possibilities to differentiate the CO_2 emission reduction between CO_2-intensive and non-CO_2-intensive sectors on required R&D subsidies (lower graph) and discounted utility (upper graph). We obtain Figure 2 in a similar fashion as Figure 1 except that we now compute R&D subsidy rates instead of shadow prices of CO_2 emissions in general equilibrium. Finally, the left dashed vertical line represents the set of uniform R&D subsidies and the right dashed vertical line represents the set of differentiated R&D subsidies.

Insert Figure 2 here

We find that R&D subsidies can also achieve the 10 percent emission reduction in production. In fact, differentiating R&D subsidies toward non-CO_2 intensive sectors not only can reduce emissions but also increases welfare compared to the reference case. Table 1 shows that compared to the hypothetical reference case, however, using R&D subsidies to achieve the emission reduction always entails a welfare loss as R&D subsidies are a first-best instrument to internalize technology externalities but a second-best instrument to reduce emissions.

Insert Table 1 here

The cost-effective set of R&D subsidies yields a welfare gain of 11.3 percent over the time period and comprises an R&D subsidy of 48 percent in the non-CO_2-intensive sectors and an R&D *tax* of 50 percent in the CO_2-intensive sectors. Although the introduction of an R&D subsidy in the non-CO_2-intensive sectors has a negative effect on CO_2 emissions because of substitution effects in production and consumption, the R&D subsidy also gives rise to a strong rebound effect that offsets the substitution effects. As the R&D subsidy lowers the marginal costs of non-CO_2-intensive goods, it indirectly increases demand for these goods and the concomitant demand for energy and CO_2 emissions. More importantly, by internalizing some of the technology externalities as well, the R&D subsidy increases welfare leading to an overall higher demand for energy and CO_2 emissions that strengthens the rebound effect. If R&D subsidies are the sole instruments of choice, an R&D *tax* in CO_2-intensive sectors is thus preferred in the cost-effective solution to keep overall emissions within bounds.[6] Essentially, the policy is one of supporting growth of non-CO_2 intensive sectors while slowing it in CO_2-intensive sectors. Introducing R&D subsidies in all sectors is feasible albeit cost ineffective in achieving the emission reduction.

Simulation 3: Combinations of differentiated CO_2-emission constraints and differentiated R&D subsidies

We next study combinations of CO_2 emission constraints and R&D subsidies as our instruments to abate CO_2 emissions in production by 10 percent relative to the reference case. For this purpose, we augment the first simulation by introducing combinations of differentiated R&D subsidies before computing the general equilibrium associated with each differentiation of the CO_2 emission constraints. This way we can identify both the cost-effective set of differentiated CO_2 emission constraints and the efficient set of differentiated R&D subsidies. Figure 3 shows effects of the various possibilities to differentiate the CO_2 emission constraint between CO_2-intensive- and non-CO_2-intensive sectors on shadow prices of CO_2 emissions in the sectors (lower graph) and discounted utility (upper graph) when the efficient set of R&D subsidies is introduced next to the CO_2-emission constraints.

Insert Figure 3 here

Emission reduction is cost effective if R&D subsidies complement rather than substitute for CO_2 emission constraints. The cost-effective set of instruments yields a welfare gain of 27.1 percent over the time period and comprises R&D subsidies of 62 percent and 53 percent in the CO_2-intensive and non-CO_2-intensive sectors as well as shadow prices of €18.60 and €9.30 per ton CO_2 in the respective sectors. Of course, the emission reduction still comes at a cost when compared to the hypothetical reference case in which we would already correct for the technology

[6] This finding is in line with other studies. Popp (2004), for example, finds that subsidizing energy R&D yields significant increases in energy technology but nevertheless has little effect on CO_2 emissions.

externalities (see Table 1). Compared with this hypothetical case, welfare falls by 1.25 percent over the time period, which is significantly more than the 0.28 percent welfare loss in the case where we do not yet make such a correction (see the first simulation). The CO_2 emission constraints are more binding when the technology externalities are already corrected and hence they entail a bigger deadweight loss.

Regarding differentiation of the policy instruments, we find that continued differentiation remains a feature of the cost-effective policy in this simulation because of interacting policy effects. The CO_2 emission constraints are principally introduced to reduce emissions but also induce technical change and concomitant technology externalities. Similarly, R&D subsidies correct for the technology externalities but at the same time affect CO_2 emissions. The R&D subsidies are now differentiated toward CO_2-intensive sectors, as they are in the hypothetical reference case in which we just correct technology externalities without regard for emission reduction, and subsequently direct technical change toward these sectors. CO_2 shadow prices remain differentiated in this simulation as technology externalities, and hence the opportunity costs of abatement, remain higher in non-CO_2 intensive sectors because of their initial size and knowledge intensity. Compared to the first simulation though, the difference in shadow prices narrows while shadow prices increase in magnitude because of the CO_2-emission constraints being more binding.

Macro-economic effects

Table 2 shows that the three simulations have different macro-economic effects besides having different welfare implications. Contracted growth characterizes the first simulation with CO_2 emission constraints. Total output growth is negative relative to the reference case, where CO_2-intensive sectors decrease their production relatively more as they are subject to the more stringent CO_2-trading scheme. Exceptions are non-CO_2 intensive industries and services and non-CO_2 intensive electricity, which slightly increase their production. With respect to inputs to production, the factor substitution effect in production increases marginal returns to factors other than energy, where the marginal return to physical capital increases to the extent that investments in physical capital actually increase slightly relative to the reference case. Foreign investment changes accordingly. International trade in goods falls proportionally to domestic trade as we assume trading partners of The Netherlands to introduce similar CO_2 emissions abatement policies. Biased growth characterizes the second simulation with R&D subsidies. By using R&D subsidies in non-CO_2 intensive sectors and R&D taxes in CO_2-intensive sectors, one speeds up growth in the former while slowing it in the latter. The production structure, for example, shifts markedly from CO_2-intensive to non-CO_2-intensive goods. Although increased welfare and limited substitution possibilities in the economy lessen the negative impact for the CO_2-intensive sectors for the first half of the model horizon, these sectors are hit hard afterwards when more substitution has been taking place and path dependency in technical change is strong. Further, more physical capital is required to expand the non-CO_2-intensive sectors and as a result investments in physical capital increase. Foreign investments change accordingly. Finally, more goods are now imported and fewer goods exported. Enhanced growth characterizes the third simulation with both CO_2 emission constraints and R&D subsidies. Because of the introduction of R&D subsidies in all sectors, total factor productivity and hence production levels increase throughout the economy relative to the reference case. As a result, demand for production factors increases as is reflected in, among others, increased investment in physical capital. Foreign investments and international trade in goods change accordingly.

Insert Table 2 here

Sensitivity analysis

Table 3 reports the sensitivity of our results to key parameter values. We use central parameter values in all sensitivity simulations (see Tables A.5-6) except for the parameter subject to analysis. Given the importance of technical change for our findings, we focus on technology parameters, which simultaneously are a good proxy for the knowledge-capital accounting. Effects are reported as index values compared to the regular simulations.

Insert Table 3 here

The general result from Table 5.4 is that our findings are robust to the range of parameter values considered. The cost-effective set of instruments still includes R&D subsidies as complements to, rather than substitutes for, CO_2-trading schemes while the cost-effective differentiation remains unchanged (no index value changes sign).

Turning to the specific parameters subject to analysis, lowering the depreciation rate of knowledge capital (δ^H) by 25 percent has a negative effect on intertemporal utility in all simulations as fewer investments in knowledge capital are required yielding less positive feedback in TC.[7] The overall decrease of technology externalities reduces the relative opportunity

[7] At the same time, lower depreciation rates lead to bigger stocks of knowledge capital yielding more knowledge spillovers. This positive welfare effect, however, is outweighed by the negative welfare effect of less positive feedback in technical change.

cost of CO_2 abatement in the non-CO_2 intensive sectors and hence the cost-effective differentiation of the CO_2-trading schemes in the first and third simulation. In the second simulation, the gap between R&D subsidies widens as R&D subsidy rates fall relatively more in non-CO_2 intensive sectors. Bigger stocks of knowledge capital enhance total factor productivity and the rebound effect, *ceteris paribus*. It therefore is cost effective to further differentiate R&D subsidies to keep emissions within bounds. The opposite holds if we increase the depreciation rate of knowledge capital by 25 percent.

Lowering the positive-feedback effect in TC (ξ) by 25 percent has a negative effect on intertemporal utility in all simulations as fewer technology externalities are enjoyed. The decrease of technology externalities reduces the relative opportunity cost of CO_2 abatement in non-CO_2 intensive sectors and hence the cost-effective differentiation of R&D subsidies in the second simulation and of CO_2-trading schemes in the third simulation. As R&D subsidies fall relatively more in non-CO_2 intensive sectors in the third simulation, the gap between R&D subsidies widens. The opposite holds if we increase the positive-feedback effect by 25 percent.

Specifying a positive feedback in TC to operate across rather than within sectors has a small negative effect on intertemporal utility, especially in the second simulation, as technology externalities in the non-CO_2 intensive sectors now also benefit CO_2-intensive sectors requiring a higher R&D tax in the latter to keep emissions within bounds. Consequently, the cost-effective differentiation of R&D subsidies widens in the second simulation. In the first and third simulations, however, the cost-effective differentiation of both policy instruments narrows as positive feedback benefits all sectors while the policy instruments are used for their first-best purpose.

Finally, lowering the substitution elasticity between knowledge capital and other factors in production (σ^H) by 25 percent has a negative effect on intertemporal utility in especially the second- and third simulations as substitution possibilities to adjust to the CO_2 abatement are limited. Moreover, the limited substitution possibilities translate into lower demands for knowledge capital and therefore fewer technology externalities. Consequently, changes in model results are similar to the analysis in which we changed the height of the positive-feedback effect.

5. Conclusions

Recent interest has arisen with respect to the role of induced innovation in environmental policy, particularly regarding climate change. The Kyoto Protocol that many industrial countries are pursuing relies on a conventional cap and trade system to constrain emissions. The US has withdrawn and has instead adopted technology policy as an alternative strategy with the intent of directing R&D to reduce CO_2 emissions. The questions we addressed in this paper are: Which strategy is preferred from a welfare perspective or does a combination of both strategies work better? Can one improve on uniform emission-reduction policy by differentiating policy toward CO_2-intensive sectors?

To answer these questions, we developed a forward-looking computable general equilibrium model that captures empirical links between CO_2 emissions associated with energy use, directed technical change and the economy. Environmental quality does not enter the utility function, implying independence of the demand functions for goods with respect to environmental quality. We specified technologies as knowledge capital, which are sector-specific investment goods and which empirical research has long found to cause positive technology externalities leading to underinvestment relative to what is socially optimal.

At this point, it is necessary to add some policy reality to the discussion. If policies can be designed to correct for technology externalities the economy can gain substantially. We show this to be the case, such that welfare in the Dutch economy under study can be improved by nearly 30 percent over our 27-year time span. We find that R&D subsidies that are optimally differentiated to achieve a 10 percent reduction in CO_2 emissions improve the economy by about 11 percent relative to the reference case where technology externalities are not yet internalized. This appears to be a double-dividend world where CO_2 emissions are reduced while leaving the economy better off. The difficulty, however, is how to design such technology policy in reality. The unrealized 30 percent welfare gain from the technology externalities is evidence of the difficulty of correcting for them. Our best past efforts, patent protection and government funded R&D, leave us with significant underinvestment. To realize the emission reduction requires that we overcome the known limits of government funding and intellectual property rights protection and then direct technology policy toward non-CO_2-intensive sectors. Our results suggest that the differential policy to achieve the emission reduction needs to be very strong. Essentially, it means creating disincentives for R&D in CO_2-intensive sectors causing them to wither away, and creating large subsidies for non-CO_2-intensive sectors, accelerating their growth. If it is possible to ideally correct for the technology externalities, we find that the preferred policy is to do so in combination with CO_2 emission constraints, *i.e.* cap and trade systems. These constraints are costly to the economy relative to the case where technology externalities are corrected for without reducing emissions, but a combination is much preferred to R&D subsidies alone or emission constraints alone.

Regardless of the particular instruments chosen, we find that technology externalities call for differentiation of instruments between non-CO_2-intensive and CO_2-intensive sectors, such that the latter bear relatively more of the abatement burden. Essentially such differentiation partly corrects for the CO_2 implications of the technology externalities. The welfare gain for differentiated emission constraints is relatively small compared with uniform constraints. The gain is large for the differentiation of R&D subsidies; in fact, uniform R&D subsidies are negative in all sectors, essentially slowing economic growth to achieve the emission reduction with highly negative welfare effects relative to the reference case or the cases involving emission constraints.

Thus, is a true double dividend possible? In principle differentiated R&D subsidies with or without CO_2 emission constraints lead to that result, relative to the reference case. However, if we can design such precise incentives for R&D we might as well compare our situation to a reference case where technology externalities are already corrected without regard to emission reduction. Compared to the “R&D corrected” reference case, emission constraints entail a larger welfare loss than does the “emission constraints only case” relative to the reference case where technology externalities are not yet corrected. So, the answer depends in part on perspective and in large part on the confidence one has that public policy can effectively direct R&D.

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Appendix A. Structure and parameter values of the model

This appendix provides an algebraic summary of the model. We formulate the model as a mixed-complementarity problem using the Mathematical Programming System for General Equilibrium Analysis (Rutherford, 1999), which is a subsystem of the General Algebraic Modeling System (Ferris and Munson, 2000). In this approach, three classes of equilibrium conditions characterize an economic equilibrium: zero-profit conditions for production activities, market clearance conditions for each primary factor and good, and an income definition for the representative consumer. The fundamental unknowns of the system are activity levels, market prices, and the income level. The zero profit conditions exhibit complementary slackness with respect to associated activity levels, the market clearance conditions with respect to market prices, and the income definition equation with respect to the income of the representative consumer. The notation Π^z denotes the zero profit condition for activity z and the orthogonality symbol $\perp$ associates variables with complementary slackness conditions. For the sake of transparency, we use the acronyms CES (constant elasticity of substitution), CD (Cobb Douglas), and LT (Leontief) to indicate functional form. Differentiating profit and expenditure functions with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's lemma), which appear subsequently in the market clearance conditions. An equilibrium allocation determines production levels, relative prices, and incomes. We choose the price of intertemporal utility as numeraire and report all prices in present values. Tables A.1 through A.6 list the nomenclature.

A.1. Zero profit conditions

Production of goods:

$$\Pi_{i,t}^{Y} \equiv \overline{H}_{i,t}^{-\gamma}\ CES\left(r_{i,t}^{H}, p_{i,t}^{KLEM}; \sigma^{H}\right) - p_{i,t} \geq 0 \qquad \perp Y_{i,t} \qquad i = 1,..,I\ ;\ t = 1,..,T \qquad \text{(A.1)}$$

where

$$p_{i,t}^{KLEM} = CES\left(p_{i,t}^{A}, CES\left(p_{i,t}^{KE}, w_t; \sigma_i^{KLE}\right); \sigma_i^{KLEM}\right)$$

$$p_{i,t}^{KE} = CES\left(r_t^{K}, CES\left(p_t^{EL}, p_{i,t}^{FF}; \sigma_i^{E}\right); \sigma_i^{KE}\right)$$

$$p_{i,t}^{FF} = LT\left(p_{NRG,t}, p_{NCI}^{EM}\right) \qquad i = AGR, SER$$

$$p_{i,t}^{FF} = LT\left(p_{NRG,t}, p_{CI}^{EM}\right) \qquad i = TT, NRG$$

$$p_{i,t}^{FF} = CES\left(LT\left(p_{NRG,t}, p_{CI}^{EM}\right), LT\left(p_t^{COAL}, p_{CI}^{EM}\right); \sigma_i^{FF}\right) \quad i = CII, CIE$$

Aggregate production of electricity:

$$\Pi_t^{EL} \equiv CES\left(p_{i,t}; \sigma^{EL}\right) - p_t^{EL} \geq 0 \qquad \perp EL_t \qquad i \in EL\,;\ t = 1,..,T \qquad \text{(A.2)}$$

Investments in knowledge capital:

$$\Pi_{i,t}^{R} \equiv \overline{R}_{i,t-1}^{-\xi}\, p_{i,t}\left(1 - s^c\right) - p_{i,t+1}^{H} = 0 \qquad \perp R_{i,t} \qquad i \in c\,;\ t = 1,..,T-1 \qquad \text{(A.3)}$$

$$\Pi_{i,T}^{R} \equiv \overline{R}_{i,T-1}^{-\xi}\, p_{i,T}\left(1 - s^c\right) - p_i^{TH} = 0 \qquad \perp R_{i,T} \qquad i \in c$$

Stock of knowledge capital:

$$p_{i,t}^{H} = r_{i,t}^{H} + \left(1 - \delta^H\right) p_{i,t+1}^{H} \qquad \perp H_{i,t} \qquad i = 1,..,I\,;\ t = 1,..,T-1 \qquad \text{(A.4)}$$

$$p_{i,T}^{H} = r_{i,T}^{H} + p_i^{TH} \qquad \perp H_{i,T} \qquad i = 1,..,I$$

Investments in physical capital:

$$\Pi_t^{I} \equiv CD\left(p_{i,t}, CES\left(r_t^K, p_t^{FDI}; \sigma^A\right)\right) - p_{t+1}^{K} = 0 \qquad \perp I_t \qquad t = 1,..,T-1 \qquad \text{(A.5)}$$

$$\Pi_T^{I} \equiv CD\left(p_{i,T}, CES\left(r_T^K, p_T^{FDI}; \sigma^A\right)\right) - p^{TK} = 0 \qquad \perp I_T$$

Stock of physical capital:

$$p_t^{K} = r_t^{K} + \left(1 - \delta^K\right) p_{t+1}^{K} \qquad \perp K_t \qquad t = 1,..,T-1 \qquad \text{(A.6)}$$

$$p_T^{K} = r_T^{K} + p^{TK} \qquad \perp K_T$$

Armington aggregate:

$$\Pi_{i,t}^{A} \equiv CES\left(p_{i,t}^{IM}, CES\left(p_{j,t}; \sigma_i^M\right); \sigma^A\right) - p_{i,t}^{A} \geq 0 \qquad \perp A_{i,t} \qquad \begin{cases} i = 1,..,I;\ j \notin E; \\ t = 1,..,T \end{cases} \qquad \text{(A.7)}$$

Imports of goods:

$$\Pi_{i,t}^{IM^Y} \equiv p_t^{FX} - p_t^{IM} \geq 0 \qquad \perp IM_{i,t}^Y \qquad i = 1,..,I\ ;\ t = 1,..,T \qquad \text{(A.8)}$$

Imports of coal:

$$\Pi_t^{IM^{COAL}} \equiv p_t^{FX} - P_t^{COAL} \geq 0 \qquad \perp IM_t^{COAL} \qquad t = 1,..,T \qquad \text{(A.9)}$$

Foreign direct investment:

$$\Pi_t^{FDI} \equiv p_t^{FX} - p_t^{FDI} \geq 0 \qquad \perp FDI_t \qquad t = 1,..,T \qquad \text{(A.10)}$$

Exports of goods:

$$\Pi_t^{EX^Y} \equiv CD\left(p_t^{EL}, p_{i,t}\right) - p_t^{FX} \geq 0 \qquad \perp EX_t^Y \qquad i \notin EL\ ;\ t = 1,..,T \qquad \text{(A.11)}$$

Exports of physical capital:

$$\Pi_t^{EX^K} \equiv r_t^K - p_t^{FX} \geq 0 \qquad \perp EX_t^K \qquad t = 1,..,T \qquad \text{(A.12)}$$

Intratemporal utility:

$$\Pi_t^W \equiv CES\left(p_t^{FX}, CES\left(p_{j,t}, p_t^E; \sigma_W^{YE}\right); \sigma^A\right) - p_t^W \geq 0 \qquad \perp W_t \qquad j \notin E\ ;\ t = 1,..,T \qquad \text{(A.13)}$$

where

$$p_t^E = CES\left(p_t^{EL}, LT\left(p_{NRG,t}, p_W^{EM}\right); \sigma_W^E\right)$$

Intertemporal utility:

$$\Pi^U \equiv CES\left(p_t^W; \rho\right) - p^U = 0 \qquad \perp U \qquad \text{(A.14)}$$

A.2. Market clearing conditions

Goods:

$$Y_{j,t} = \frac{\partial \Pi_{i,t}^R}{\partial p_{j,t}} R_{j,t} + \frac{\partial \Pi_t^I}{\partial p_{j,t}} I_t + \sum_i \frac{\partial \Pi_{i,t}^A}{\partial p_{j,t}} A_{i,t} + \frac{\partial \Pi_t^W}{\partial p_{j,t}} W_t + \frac{\partial \Pi_t^{EX^Y}}{\partial p_{j,t}} EX_t^Y \quad \perp p_{j,t} \quad j \notin E\ ;\ t = 1,..,T \quad \text{(A.15)}$$

$$Y_{j,t} = \frac{\partial \Pi_{i,t}^R}{\partial p_{j,t}} R_{j,t} + \frac{\partial \Pi_t^I}{\partial p_{j,t}} I_t + \sum_i \frac{\partial \Pi_{i,t}^Y}{\partial p_{j,t}} Y_{i,t} + \frac{\partial \Pi_t^W}{\partial p_{j,t}} W_t + \frac{\partial \Pi_t^{EX^Y}}{\partial p_{j,t}} EX_t^Y \quad \perp p_{j,t} \quad j = NRG\ ;\ t = 1,..,T$$

$$Y_{j,t} = \frac{\partial \Pi_{i,t}^R}{\partial p_{j,t}} R_{j,t} + \frac{\partial \Pi_t^I}{\partial p_{j,t}} I_t + \frac{\partial \Pi_t^{EL}}{\partial p_{j,t}} EL_t \quad \perp p_{j,t} \quad j \in EL\ ;\ t = 1,..,T$$

Electricity:

$$EL_t = \sum_i \frac{\partial \Pi_{i,t}^Y}{\partial p_t^{EL}} Y_{i,t} + \frac{\partial \Pi_t^{EX^Y}}{\partial p_t^{EL}} EX_t^Y + \frac{\partial \Pi_t^W}{\partial p_t^{EL}} W_t \quad \perp p_t^{EL} \quad t = 1,..,T \quad \text{(A.16)}$$

Knowledge capital (in market):

$$\frac{r_{i,t}^H H_{i,t}}{r + \delta^H} = \frac{\partial \Pi_{i,t}^Y}{\partial r_{i,t}^H} Y_{i,t} \quad \perp r_{i,t}^H \quad i = 1,..,I\ ;\ t = 1,..,T \quad \text{(A.17)}$$

Knowledge capital (in stock):

$$H_{i,t=1} = H_{0i} \quad \perp p_{i,t=1}^H \quad i = 1,..,I \quad \text{(A.18)}$$

$$H_{i,t} = \left(1 - \delta^H\right) H_{i,t-1} + R_{i,t-1} \quad \perp p_{i,t}^H \quad i = 1,..,I\ ;\ t = 2,..,T$$

$$TH_i = \left(1 - \delta^H\right) H_{i,T} + R_{i,T} \quad \perp p_i^{TH} \quad i = 1,..,I$$

Physical capital (in market):

$$\frac{r_t^K K_t}{r + \delta^K} = \frac{\partial \Pi_t^I}{\partial r_t^K} I_t + \sum_i \frac{\partial \Pi_{i,t}^Y}{\partial r_t^K} Y_{i,t} + \frac{\partial \Pi_t^{EX^K}}{\partial r_t^K} EX_t^K \quad \perp r_t^K \quad t = 1,..,T \quad \text{(A.19)}$$

Physical capital (in stock):

$$K_{t=1} = K_0 \qquad \perp p^K_{t=1} \tag{A.20}$$

$$K_t = \left(1-\delta^K\right) K_{t-1} + I_{t-1} \qquad \perp p^K_t \qquad t = 2,..,T$$

$$TK = \left(1-\delta^K\right) K_T + I_T \qquad \perp p^{TK}$$

Labor:

$$L_t = \sum_i \frac{\partial \Pi^Y_{i,t}}{\partial w_t} Y_{i,t} \qquad \perp w_t \qquad t = 1,..,T \tag{A.21}$$

Coal (imports):

$$IM^{COAL}_t = \sum_i \frac{\partial \Pi^Y_{i,t}}{\partial p^{COAL}_t} Y_{i,t} \qquad \perp p^{COAL}_t \qquad t = 1,..,T \tag{A.22}$$

Import aggregate:

$$IM^Y_{i,t} = \frac{\partial \Pi^A_{i,t}}{\partial p^{IM}_{i,t}} A_{i,t} \qquad \perp p^{IM}_{i,t} \qquad i = 1,..,I\ ;\ t = 1,..,T \tag{A.23}$$

Armington aggregate:

$$A_{i,t} = \frac{\partial \Pi^Y_{i,t}}{\partial p^A_{i,t}} Y_{i,t} \qquad \perp p^A_{i,t} \qquad i = 1,..,I\ ;\ t = 1,..,T \tag{A.24}$$

Foreign investments:

$$FDI_t = \sum_i \frac{\partial \Pi^I_t}{\partial p^{FDI}_t} I_t \qquad \perp p^{FDI}_t \qquad t = 1,..,T \tag{A.25}$$

Foreign exchange:

$$\begin{aligned} BOP_t &= \frac{\partial \Pi_t^{EX^Y}}{\partial p_t^{FX}} EX_t^Y + \frac{\partial \Pi_t^{EX^K}}{\partial p_t^{FX}} EX_t^K - \sum_i \frac{\partial \Pi_{i,t}^{IM^Y}}{\partial p_t^{FX}} IM_{i,t}^Y \\ &\quad - \frac{\partial \Pi_t^{IM^{COAL}}}{\partial p_t^{FX}} IM_t^{COAL} - \frac{\partial \Pi_t^{FDI}}{\partial p_t^{FX}} FDI_t - \frac{\partial \Pi_t^W}{\partial p_t^{FX}} W_t \end{aligned} \quad \perp p_t^{FX} \qquad t = 1,..,T \qquad \text{(A.26)}$$

CO_2 emissions in consumption:

$$EM_W = \sum_t \frac{\partial \Pi_t^W}{\partial p_W^{EM}} W_t \qquad \perp p_W^{EM} \qquad \text{(A.27)}$$

CO_2 emissions in production:

$$EM_c = \sum_i \sum_t \frac{\partial \Pi_{i,t}^Y}{\partial p_c^{EM}} Y_{i,t} \qquad \perp p_c^{EM} \qquad c = CI, NCI \qquad \text{(A.28)}$$

Intratemporal utility:

$$W_t = \frac{\partial \Pi^U}{\partial p_t^W} U \qquad \perp p_t^W \qquad t = 1,..,T \qquad \text{(A.29)}$$

Intertemporal utility:

$$U = \frac{B}{p^U} \qquad \perp p^U \qquad \text{(A.30)}$$

A.3. Income balance

$$\begin{aligned} B &= \sum_i \left(H_{i,0} - p_i^{TH} TH_i \right) + K_0 - p^{TK} TK + \sum_t w_t L_t + \sum_c p_c^{EM} EM_c \\ &\quad - \sum_c \sum_t s^c \frac{\partial \Pi_{i,t}^R}{\partial p_{i,t}} R_{i,t} + \sum_t p_t^{FX} BOP_t \end{aligned} \qquad \text{(A.31)}$$

A.4. Endowments

Supply of labor:

$$L_t = \left(1 + g\right)^{t-1} L_0 \qquad t = 1,..,T \qquad \text{(A.32)}$$

Balance of Payments:

$$BOP_t = (1+g)^{t-1} BOP_0 \qquad t = 1,..,T \qquad \text{(A.33)}$$

A.5. Constraints

CO_2 emission constraint of environmental policy in consumption:

$$EM_W = (1-a)\sum_t (1+g)^{t-1} EM_{0W} \qquad \text{(A.34)}$$

CO_2 emission constraint of environmental policy in production in simulations 1 and 3:

$$EM_c = \left(1-a^c\right)\sum_t (1+g)^{t-1} EM_{0c} \qquad c = CI, NCI \qquad \text{(A.35)}$$

where:

$$a\ EM = \sum_c EM_c$$

and in simulation 2:

$$EM_c = \sum_t (1+g)^{t-1} EM_{0c} \qquad c = CI, NCI$$

CO_2-emission constraint of technology policy in simulation 2:

$$\sum_i \sum_t \frac{\partial \Pi_{i,t}^Y}{\partial p_c^{EM}} Y_{i,t} \le \left(1-a^c\right) EM_c \qquad \perp s^c \qquad c = CI, NCI \qquad \text{(A.36)}$$

where:

$$a\ EM = \sum_c \left(1-a^c\right) EM_c$$

and in simulation 3:

$$\sum_i \sum_t \frac{\partial \Pi_{i,t}^Y}{\partial p_c^{EM}} Y_{i,t} \le EM_c \qquad \perp s^c \qquad c = CI, NCI$$

Terminal condition for physical capital:

$$\frac{I_T}{I_{T-1}} = \frac{W_T}{W_{T-1}} \qquad \perp TK \qquad \text{(A.37)}$$

Terminal condition for physical capital:

$$\frac{R_{i,T}}{R_{i,T-1}} = \frac{W_T}{W_{T-1}} \qquad \perp TH_i \qquad \text{(A.38)}$$

A.6. Nomenclature

Table A.1: Sets and indices

i	$AGR, IND, TT, SER, NRG, CIE, NCIE$	Sectors and goods (aliased with *j*)
E	$NRG, CIE, NCIE$	Energy (sectors)
EL	$CIE, NCIE$	Electricity (sectors)
FF	$COAL, NRG$	Fossil fuel (sectors)
c	$CI: IND, TT, NRG, CIE$ $NCI: AGR, SER, NCIE$	Sectors according to CO_2 intensity
t	$1,..,T$	Time periods

Table A.2: Activity variables

$Y_{i,t}$	Production of goods in sector *i* at time *t*
EL_t	Aggregate production of electricity at time *t*
$H_{i,t}$	Stock of knowledge capital in sector *i* at time *t*
$\overline{H}_{i,t}$	Knowledge spillover applied to sector *i* at time *t*
TH_i	Terminal stock of knowledge capital in sector *i*
$R_{i,t}$	Investments in knowledge capital in sector *i* at time *t*
$\overline{R}_{i,t}$	Feedback in technical change applied to sector *i* at time *t*
K_t	Stock of physical capital at time *t*
TK	Terminal stock of physical capital
I_t	Investments in physical capital at time *t*
$A_{i,t}$	Armington aggregate of domestic- and foreign intermediate goods in sector *i* at time *t*
$IM_{i,t}^{Y}$	Aggregate imports of goods in sector *i* at time *t*
IM_t^{COAL}	Aggregate imports of coal at time *t*

FDI_t	Foreign direct investment at time *t*
EX_t^Y	Aggregate exports of goods at time *t*
EX_t^K	Aggregate exports of physical capital at time *t*
W_t	Intratemporal utility at time *t*
U	Intertemporal utility

Table A.3: Income- and endowment variables

B	Budget of the representative agent
BOP_0	Initial Balance of Payments of the domestic representative agent
BOP_t	Balance of Payments of the domestic representative agent at time *t*
H_{0i}	Initial stock of knowledge capital in sector *i*
K_0	Initial stock of physical capital
L_0	Initial endowment of labor
L_t	Endowment of labor at time *t*
EM_0	Initial allowances of CO_2 emissions
EM	Overall allowances of CO_2 emissions

Table A.4: Price variables (in present values)

p	Prices
p_t^{FX}	Price of foreign exchange at time *t*
p^{EM}	Shadow prices of CO_2 emissions
s^c	Subsidy on investments in knowledge capital in sectors *c*
r_t	Rental rate of capital at time *t*
w_t	Wage rate at time *t*

Table A.5: Parameters

Description		Value
a	Abatement of CO_2 emissions	0.10
γ	Knowledge spillover coefficient	0.09
ξ	Coefficient of positive feedback in technical change	0.20
g	Growth rate	0.02
r	Interest rate	0.05
δ^K	Depreciation rate of physical capital	0.05
δ^H	Depreciation rate of knowledge capital	0.25

Table A.6: Elasticities

Description									Value
Elasticity of substitution in intertemporal utility									
ρ	Between time periods								0.5
Elasticities of substitution in intratemporal utility									
σ_W^{YE}	Between energy and other goods								0.5
σ_W^{E}	Between electricity and fossil fuels								0.7
Elasticities of substitution in international trade									
σ^{A}	Between domestic and foreign commodities								1.0
Elasticities of substitution in aggregate electricity production									
σ^{EL}	Between CO_2-intensive and non-CO_2 intensive electricity								2.5

Elasticities of substitution in production sector		AGR	IND	TT	SER	NRG	CIE	NCIE
σ^{H}	Between knowledge capital and remaining inputs	1.0	1.0	1.0	1.0	1.0	1.0	1.0
σ_i^{KLEM}	Between intermediate inputs and remaining inputs	0.4	0.5	0.7	0.7	0.9	0.1	0.1
σ_i^{M}	Between intermediate inputs	0.1	0.2	0.3	0.3	0.5	0.1	0.1
σ_i^{KLE}	Between labor and remaining inputs	0.3	0.2	0.4	0.4	0.5	0.1	0.1
σ_i^{KE}	Between physical capital and energy	0.7	0.7	0.7	0.7	0.1	0.7	0.7
σ_i^{E}	Between electricity and fossil fuels	0.5	0.5	0.5	0.5	0.1	0.5	
σ_i^{FF}	Between fossil fuels	0.9	0.9	0.9	0.9	0.1	0.5	

Notes: The substitution elasticities in utility are assumed. The substitution elasticity in intertemporal utility lies between smaller values typically found in time-series studies (*e.g.* Hall, (1988) and larger values typically found in studies that also exploit cross-sectional data (*e.g*. Beaudry and Wincoop, 1996). The substitution elasticity in international trade is lower than usual to reflect introduction of similar CO_2 emission reduction policies by most of the trading partners of The Netherlands. We obtain the substitution elasticities in production from the TaxInc model (Statistics Netherlands, 1990), except for the substitution elasticity between knowledge capital and remaining inputs, which we obtain from Goulder and Schneider (1999), and except the substitution elasticity in aggregate electricity production, which is assumed.

Appendix B. Data

Table B.1: Cost- and market shares of electricity technologies (%)

	Cost shares					Market share
	Physical Capital	Labor	Energy	Intermediate inputs	Total	
CO_2 intensive						
Natural-gas fired	24.9	5.6	62.2	7.3	100.0	56.9
Hard-coal fired	38.6	5.6	23.7	9.0	76.9	25.5
Oil-fired	46.9	2.2	40.3	10.6	100.0	7.6
Non-CO_2 intensive						
Biomass	18.8	6.6		58.5	83.9	4.6
Nuclear	59.0	5.1		17.4	81.5	4.4
Wind	86.4	19.8			106.2	1.0

Source: Böhringer *et al.* (2003)

Table B.2: National accounting matrix for The Netherlands in 1999 (million euro)

	Agriculture	CO_2-intensive industry	Trade and transport	Non-CO_2 intensive industry and services	Energy	CO_2-intensive electricity	Non-CO_2 intensive electricity	Exports	Consumption	Investments in physical capital	Investments in knowledge capital	Supply changes	Total
Agriculture	16.29	0.09	0.08	1.83	0.02		0.02	28.49	7.36	0.73	1.72	0.06	56.68
CO_2-intensive industry	0.87	4.92	1.43	8.63	0.14	0.05	0.07	34.66	3.96	0.28	7.31	0.01	62.31
Trade and transport	0.54	0.65	3.14	4.09	0.25	0.01	0.02	77.38	7.06	0.51	6.87	-0.01	100.50
Non-CO_2 intensive industry and services	4.23	4.71	14.64	67.09	1.16	0.64	0.08	34.45	160.94	89.36	60.46	0.16	437.92
Energy	0.99	1.08	1.50	1.23	4.31	0.83		11.42	5.38	0.07	1.07	0.08	27.97
Electricity	0.54	0.63	0.57	0.72	0.07	3.32	0.39	2.07	2.20	0.01	0.60	0.00	11.13
Imports	14.31	21.01	13.75	60.30	6.20	1.26			62.90	23.59		0.25	203.56
Taxes minus subsidies	-0.70	0.12	-0.98	4.18	4.60	0.38	0.06						7.66
Labor	5.97	10.90	33.23	133.54	1.34	0.76	0.09						185.84
Physical capital	11.72	10.09	25.52	89.12	8.69	2.16	0.31	0.56	16.96	3.50			168.63
Knowledge capital	1.92	8.12	7.63	67.18	1.19	0.60	0.07						86.71
Total	56.68	62.31	100.50	437.92	27.97	10.01	1.11	189.02	266.76	118.04	78.03	0.54	

Sources: Statistics Netherlands (2000), Böhringer *et al.* (2003), De Haan and Rooijen-Horsten (2004) and own calculations.

Table B.3: Selected factor-intensities of the Dutch economy in 1999 (% of gross sectoral product)

	Knowledge capital				Physical capital	Labor	CO_2
Sector	R&D	EDU	ICT	Total			
Production							
CO_2 intensive	3.3	4.8	0.7	8.7	23.1	23.0	0.07
CO_2-intensive industry	8.3	4.4	0.4	13.0	16.2	17.5	0.08
Trade and transport	0.8	6.2	0.6	7.6	25.4	33.1	0.04
Energy	1.8	1.3	1.3	4.3	31.1	4.8	0.04
CO_2-intensive electricity	1.3	2.4	2.3	6.0	21.6	7.6	0.41
Non-CO_2 intensive	3.7	8.7	1.5	14.0	20.4	28.2	<0.01
Agriculture	1.5	1.4	0.5	3.4	20.7	10.5	0.01
Non-CO_2 intensive industry and services	4.0	9.7	1.6	15.3	20.4	30.5	<0.01
Non-CO_2 intensive electricity	1.3	2.4	2.3	6.0	28.3	7.8	0.00
Consumption							0.01

Note: Capital intensities are respectively services derived from knowledge- and physical capital expressed as percentages of gross sectoral product. CO_2 intensities are CO_2 emissions in Mt. expressed as percentage of gross sectoral product in million euros. We obtain data on knowledge capital from De Haan and Rooijen-Horsten (2004) and data on CO_2 emissions from the GTAP-EG database (Paltsev and Rutherford, 2000) and the Emission Monitor for The Netherlands (Koch, *et al.*, 2002).

Table 1: Effects of policies on discounted utility (% change from original reference)

	% change from original reference	% change from hypothetical reference
reference cases		
original	0.00	-28.35
hypothetical with correction for technology externalities	28.35	0.00
simulations		
differentiated CO_2-emission constraints	-0.28	-28.63
differentiated R&D subsidies to reduce CO_2 emissions	11.30	-17.05
combinations of differentiated CO_2-emission constraints and differentiated R&D subsidies	27.10	-1.25

Table 2: Effects of CO_2-reduction policies on the Dutch economy (percentage changes)

		Simulation								
		1			2			3		
		2005	2015	2025	2005	2015	2025	2005	2015	2025
Production	Total	-0.4	-0.6	-0.9	31.0	43.8	44.8	48.1	78.9	98.4
CO_2 intensive	IND	-0.8	-1.5	-2.3	-9.6	-11.0	-29.5	85.9	133.1	161.9
	TT	-0.7	-1.3	-2.0	-10.1	-15.5	-39.8	35.3	60.3	74.2
	NRG	-3.5	-5.4	-8.2	-11.6	-9.3	-29.7	10.6	36.6	44.8
	CIE	-2.6	-4.2	-6.5	-12.1	-8.6	-16.0	36.3	47.6	36.3
Non-CO_2 intensive	AGR	-0.6	-1.1	-1.6	15.2	16.3	-15.3	18.5	56.6	80.3
	SER	0.1	0.2	0.2	51.8	73.2	88.6	52.3	78.6	101.6
	NCIE	3.1	5.0	8.1	88.4	105.5	74.5	25.4	119.7	258.0
Investments in knowledge capital	Total	-0.3	-0.4	-0.6	246.6	275.3	310.3	346.7	510.4	625.2
CO_2 intensive	IND	-1.0	-1.7	-2.5	-44.0	-49.5	-59.1	632.5	935.5	1156.4
	TT	-0.9	-1.6	-2.3	-43.1	-53.7	-66.7	355.9	535.9	628.3
	NRG	-4.1	-6.3	-9.0	-47.2	-48.6	-59.8	208.2	418.8	481.0
	CIE	-2.7	-4.2	-6.2	-48.3	-45.6	-48.8	361.3	478.7	447.8
Non-CO_2 intensive	AGR	-0.8	-1.3	-1.9	166.6	155.2	58.8	166.4	362.8	471.5
	SER	0.0	0.1	0.1	324.6	363.8	414.7	318.8	462.0	568.4
	NCIE	5.7	7.7	12.3	458.0	481.3	338.5	181.2	700.6	1455.5
Investments in physical capital		0.9	1.3	1.7	38.7	88.8	126.0	38.6	42.7	51.4
Exports of goods		-0.8	-1.5	-2.4	0.3	-6.3	-41.3	29.7	57.2	74.1
Imports of goods		-0.6	-1.0	-1.5	3.4	9.6	3.0	31.0	56.0	70.0
Foreign investment		0.7	1.1	1.2	12.8	52.5	79.2	38.2	43.2	51.5
Shadow price of CO_2	CI	2.8	2.8	2.8				18.6	18.6	18.6
emissions	NCI	0.1	0.1	0.1				9.3	9.3	9.3
Subsidy on investments	CI				-0.50	-0.50	-0.50	0.62	0.62	0.62
in knowledge capital	NCI				0.48	0.48	0.48	0.53	0.53	0.53

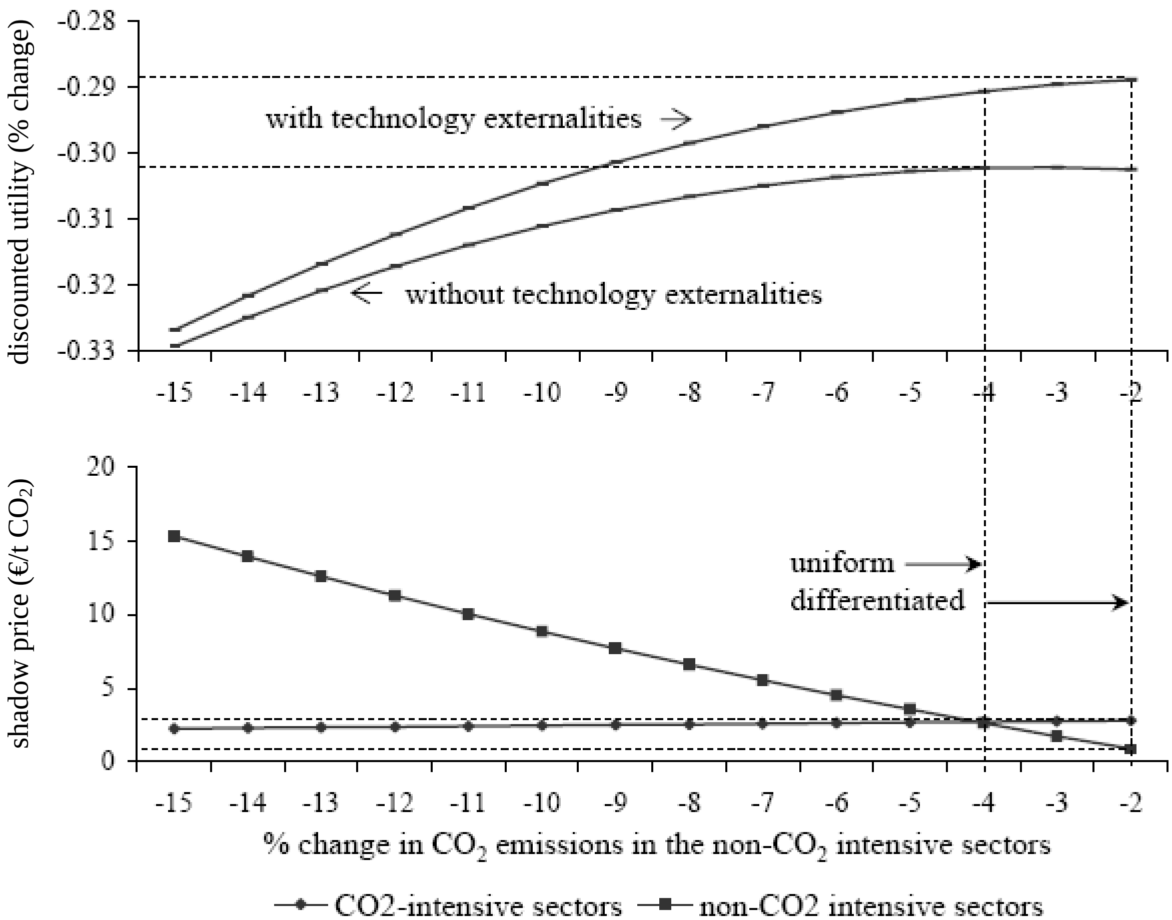
Notes: Shadow prices of CO_2 emissions are in €/t CO_2. AGR is agriculture, IND is CO_2-intensive industry, TT is the trade and transport sector, SER is non-CO_2 intensive industry and services, NRG is the energy sector, CIE is CO_2-intensive electricity and NCIE is non-CO_2 intensive electricity. CI refers to CO_2-intensive sectors and NCI to non-CO_2 intensive sectors.

Table 3: Piecemeal sensitivity analysis

		Discounted utility			Cost-effective differentiation of instruments			
		Simulation			Simulation			
		1	2	3	1	2	3	
		U	U	U	$p_{CI}^{EM} - p_{NCI}^{EM}$	$s_{CI} - s_{NCI}$	$p_{CI}^{EM} - p_{NCI}^{EM}$	$s_{CI} - s_{NCI}$
Regular simulation		1.00	1.00	1.00	1.00	1.00	1.00	1.00
δ^H	low	1.00	0.99	0.97	0.53	1.09	0.88	1.00
δ^H	high	1.00	1.01	1.02	1.00	0.92	1.09	1.00
ξ	low	1.00	0.95	0.93	1.00	0.91	0.90	1.11
ξ	high	1.00	1.09	1.13	1.00	1.09	1.16	0.78
ξ	uniform	1.00	0.99	1.00	0.69	1.52	0.92	0.89
σ^H	low	1.00	0.96	0.94	1.00	0.88	0.94	1.33
σ^H	high	1.00	1.05	1.07	1.00	1.31	1.02	0.67

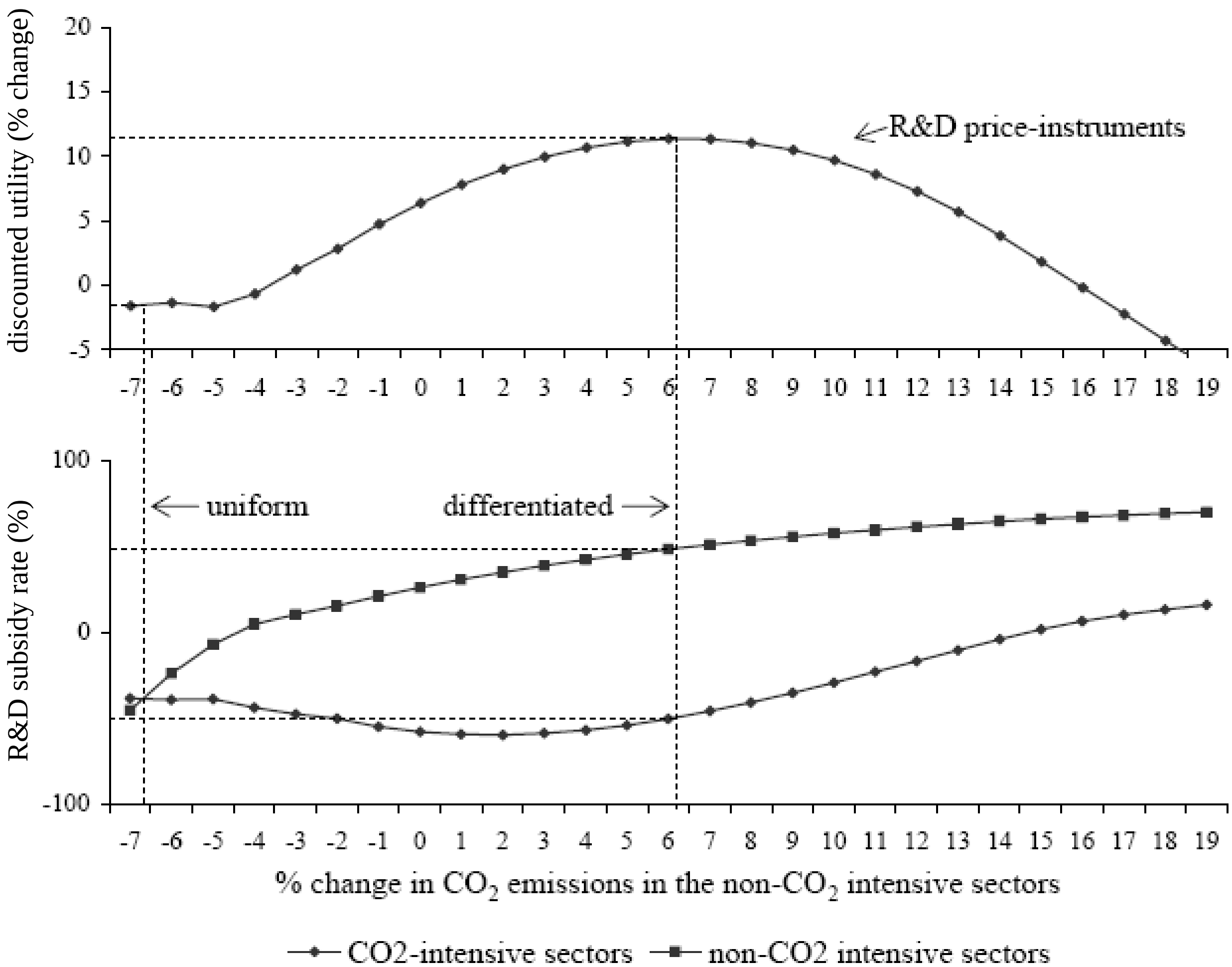
Notes: All numbers are indexed to the regular simulation. Results in simulation 1 are robust at the 1 percent precision level. Simulation 1 refers to differentiated CO_2-emission constraints; simulation 2 to differentiated R&D subsidies; simulation 3 to combinations of differentiated CO_2-emission constraints and differentiated R&D subsidies. Low and high refer to 25 percent lower and higher parameter values than in the regular simulation and uniform refers to positive feedback in technical change being specified to operate across sectors. U denotes discounted utility, p^{EM} denotes the shadow price of CO_2 emissions and s denotes the R&D subsidies.

Figure 1: Effects of differentiated CO_2-emission constraints on discounted utility



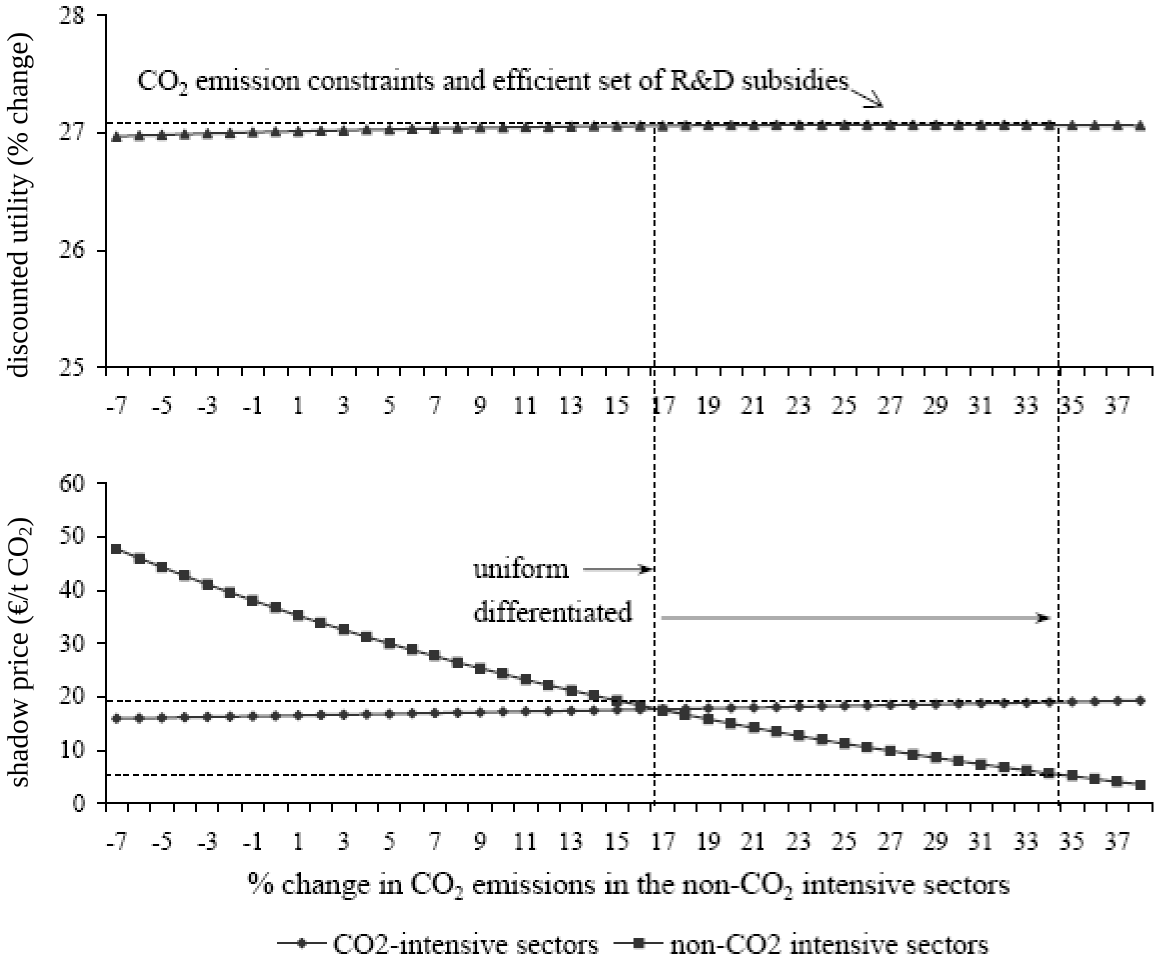
Notes: CO_2 emissions in the CO_2-intensive sectors change to the extent that overall CO_2 emissions in production are reduced by 10 percent.

Figure 2: Effects of differentiated R&D subsidies on discounted utility



Notes: CO_2 emissions in the CO_2-intensive sectors change to the extent that overall CO_2 emissions in production are reduced by 10 percent.

Figure 3: Effects of cost-effective set of differentiated CO_2 emission constraints and differentiated R&D subsidies on discounted utility



Notes: CO_2 emissions in the CO_2-intensive sectors change to the extent that overall CO_2 emissions in production are reduced by 10 percent.

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