Technology shocks and directed climate policy:
The case of CO_2 capture and storage

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Abstract

In the environmental-economics literature, it is often assumed that technical change is anticipated. In reality, however, the large uncertainties surrounding technical change cause most innovations to be unanticipated. This paper studies implications of unanticipated technical change for the design of cost-effective climate policy. For this purpose, we develop a dynamic general equilibrium model that explicitly captures empirical links between CO_2 emissions associated with energy use, directed technical change and the economy. Besides specifying incremental technical change trough investments in knowledge capital (innovation), its adoption (diffusion) and technology externalities, we introduce CO_2 capture and storage as a radical CO_2 abatement technology that becomes competitive at some point in the future. We then analyze simulations in which the competitiveness of this technology is anticipated while in others it is unanticipated. We assess uncertainties regarding the technology's costs and performance by Monte Carlo simulations. Besides showing quantitative implications for the cost-effective direction of climate policy, we show the extent to which non anticipation of the technology's competitiveness affects abatement- and innovation paths.

Keywords: CO_2 capture and storage, computable general equilibrium modeling, directed technical change, climate policy, uncertainty

JEL classification: D58, D83, H23, O33, Q43

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1. Introduction

The long-run stabilisation of GHG concentrations to lower levels requires the deployment of a portfolio of mitigation measures like energy efficiency improvements, switching to less CO_2-intensive energy sources, and the use of CO_2 capture and storage (CCS) (IPCC, 2007). While some of these options are already available, others are not. CO_2 capture and storage is a known technological option that is not yet commercial. It involves the separation and concentration of CO_2 produced in industrial and energy-related sources, the transportation to a suitable storage location (an aquifer, depleted oil field, or the ocean), and the storage preventing its release to the atmosphere for a prolong period of time. The technical maturity of the different components of the complete CCS system varies considerably: some components are already deployed in mature markets, while others are still in the research, development or demonstration phase. The maturity of the overall system may be even less since there is little experience with the assembly of all components into an integrated CCS system. There are some first pilot projects linking CO_2 capture and geological storage, but CCS technologies have not yet been applied at large fossil-fuel power plants. Large scale deployment of the CCS technology requires climate policies that substantially limit CO_2 emissions to the atmosphere (IPCC, 2005).

The large-scale deployment of the CCS technology would allow for a continued reliance on fossil fuels in the supply of primary energy while at the same time reducing CO_2 emissions over the course of this century. This explains the great interest in the potential use of CCS as a CO_2 abatement technology, which has lead to different studies using quantitative energy-economy models (see e.g. McFarland et al., 2004; Riahi et al., 2004; Popp, 2006; Otto and Reilly, 2006; Bosetti and Tavoni, 2007). Most of these studies account for technical change as an endogenous, but deterministic process. McFarland et al. (2004), for example, find that CCS technologies could play a substantial role in reducing CO_2 emissions, but only with climate policies in place. Riahi et al. (2004) analyze the potential of carbon capture and sequestration technologies in long-term energy-economic-environmental simulations based on alternative assumptions for technological progress of CCS technologies. In their simulations, CCS technologies are not static with technology costs assumed to stay constant over time, but are subject to learning-by-doing. More recently, Bosetti and Tavoni (2007) look at optimal investment and climate policy responses in a stochastic version of the energy system model WITCH when a backstop technology, i.e. a technology that is available at a constant marginal cost, is characterized by either a deterministic or an uncertain process. Popp (2006) analyzes the adoption of a backstop technology in a model with induced technological change provided via research and development in ENTICE-BR.

This paper studies the implications of unanticipated technical change for the design of cost-effective climate policy. In doing so, we differ from the previous studies mainly in two aspects: (i) Whereas most studies look at uniform climate policies, we analyse the direction of technical change in a multi-sectoral setting and look at the optimal differentiation of climate policy instruments between sectors. (ii) Most studies assume that technical change through e.g. incremental efficiency improvements or new abatement technologies is fully anticipated. In contrast we look also at the effects of unanticipated innovations, since most innovations tend to be unanticipated given the large uncertainties surrounding technical change.

For the purpose of this paper, we develop a dynamic general equilibrium model -calibrated for the Netherlands- that explicitly captures empirical links between CO_2 emissions associated with energy use, directed technical change and the economy. Besides specifying incremental technical change trough investments in knowledge capital (innovation), its adoption (diffusion) and technology externalities, we introduce CO_2 capture and storage as a radical CO_2 abatement technology that becomes competitive at some point in the future. In order to study implications of unanticipated technical change for the design of climate policy, we analyze two extreme simulations: in the first simulation the competitiveness of the CCS technology is anticipated and there is optimal adjustment by the agents (*ANT*); in the second simulation, the competitiveness constitutes a technology shock, the agents are taken by surprise and there is an unanticipated response to the new CO_2 abatement technology (*SHK*). Our analysis shows that intertemporal utility is higher if competitiveness of the CCS technology is unanticipated and that it is cost effective to differentiate the climate policy according to the relative difference in technology externalities between non-CO_2 intensive and CO_2-intensive sectors such that it is cheaper to shift some abatement toward CO_2-intensive technologies and sectors. The literature reports a fairly wide range of costs for employing CCS systems and their technological characterization. These uncertainties regarding the (cost) potential of the CCS technology matter for its competitiveness and are assessed by performing

Monte Carlo simulations. The uncertainty propagation suggests that our main results are robust.

The remainder of this paper is organized as follows. Section 2 describes the main characteristics of our dynamic general equilibrium model and the specification of technical change. Section 3 describes the knowledge capital accounting in the input-output tables underlying the CGE model, the central parameter values and data used in the model and the calibration of the CCS technology. Section 4 discusses the simulations and their results. Section 5 presents the uncertainty analysis. Section 6 concludes.

2. Model description

This section presents the main characteristics of our dynamic general equilibrium model for the Netherlands that explicitly captures links between CO_2 emissions associated with energy use, directed technical change and the economy. In the following, we provide a non-technical model overview with the basic features of the model and the specifications of technological change. We provide a full description of the model in Appendix A.

2.1. Basic features of the model

We specify several economic agents in our model: a representative consumer, representative producers of final goods in different production sectors and representative firms in intermediate sectors manufacturing sector specific knowledge capital for the respective production sectors. We distinguish between seven production sectors: agriculture, CO_2-intensive industry, non-CO_2 intensive industry and services, trade and transport, energy, CO_2-intensive electricity and non-CO_2-intensive electricity. The energy sector comprises the oil- and gas industries. Further, we label agriculture, non-CO_2 intensive industries and services, and non-CO_2-intensive electricity as non-CO_2 intensive sectors and CO_2-intensive industries, trade and transport, energy, and CO_2-intensive electricity as CO_2-intensive sectors. Imported coal is used in the production of certain CO_2-intensive goods and electricity. Primary factors include labor, physical capital and knowledge capital. We treat labor and physical capital as intersectorally mobile whereas knowledge capital is sector specific. Table 1 summarizes the sectors and primary factors in the dynamic CGE model for the Netherlands.

Table 1 Sectors and primary factors in our model

Sectors		Primary factors
CO_2 intensive		
CII	CO_2-intensive industry	Physical capital
TT	Trade and transport	Knowledge capital
NRG	Energy (comprising oil & gas industries)	Labor
CIE	CO_2-intensive electricity	
Non-CO_2 intensive		
AGR	Agriculture	
SER	Non-CO_2 intensive industry & services	
NCIE	Non-CO_2-intensive electricity	

Each agent behaves rationally and, until specified differently, has perfect foresight. The representative consumer maximizes intertemporal utility subject to the lifetime budget constraint. The intertemporal utility function is a nested constant-elasticity-of-substitution (CES) aggregate of the discounted sum of consumption of goods over the time horizon and is measured as equivalent variation (see equations A.14 and A.15 in the appendix). The model is designed to examine cost-effectiveness of abatement options. 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 CES functions of knowledge capital, physical capital, labor, and intermediate inputs (see equation A.1). 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 CO_2 abatement technology. The markets for final goods and for the production factors labor and physical capital are perfectly competitive.

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. Finally, 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.

2.2. Specification of technical change

We specify both incremental and radical technical change in our model. Incremental technical change is characterized by deterministic and continuous innovation possibility frontiers, which describe investments in and creation of knowledge capital in the different sectors (innovation) (see equation A.4). These investments merely involve final goods as input. Rivera-Batiz and Romer (1991) refer to this specification as the 'lab-equipment' specification for its emphasis on tangible inputs. As they also point out, this does not mean that final goods are directly converted into knowledge capital, but rather that the inputs necessary for production of final goods are used, in the same proportions, for innovation instead. Further, we assume knowledge capital to be 'appropriate' for the production function of a specific final good only (c.f. Basu and Weil, 1998). Hence, knowledge capital is sector specific and cannot be used in the production of final goods in other sectors. Technical change is directed to a specific sector if its investment in knowledge capital increases relative to the other sectors. 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. Rivera-Batiz and Romer (1991) dub this specification the 'knowledge-based' specification of innovation for its emphasis on intangible inputs. Knowledge spillovers and network effects, among others, underlie this technology externality. We specify this technology externality operating within each sector only, since we assume that knowledge capital in the different sectors is too different from each other to benefit from each other's technical changes. Finally, knowledge-capital investments accumulate into stocks, and we assume these give rise to an additional technology externality in sectoral production, i.e. knowledge spillovers. 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.[1]

Our specification of the production possibility frontier is similar to Goulder and Schneider (1999). Technology externalities to an individual producer in a sector are introduced by a scale factor in a CES production function that is an increasing function of intermediate sector aggregate R&D activities. 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. 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. As a result, private and social returns to knowledge capital diverge and the representative producer under-invests in knowledge capital from a social welfare perspective. To bring the private- and social returns closer together, however, investments in knowledge capital might be subject to a R&D subsidy. 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.

In addition to this incremental technical change, we introduce gas-fired electricity generation technologies with CCS (referred to as the CCS technology throughout the paper) as a radically new technology in the CO_2-intensive electricity sector. The CCS technology is considered to be a perfect substitute for those technologies without CCS, but is not yet competitive. The CCS technology is characterized by a separate constant-elasticity-of-substitution function of knowledge capital, physical capital, labor, and intermediate inputs (see equation A.2). Assuming fixed proportions between inputs other than knowledge capital ensures that the CCS technology is specified as a discrete technology (i.e. a backstop). Finally, we assume that engineers and scientists working in conventional power plants would also be involved in applying the CCS technology and the same knowledge capital is therefore used in both technologies. Figure 1 illustrates the production structure and the specification of technical change in our model.

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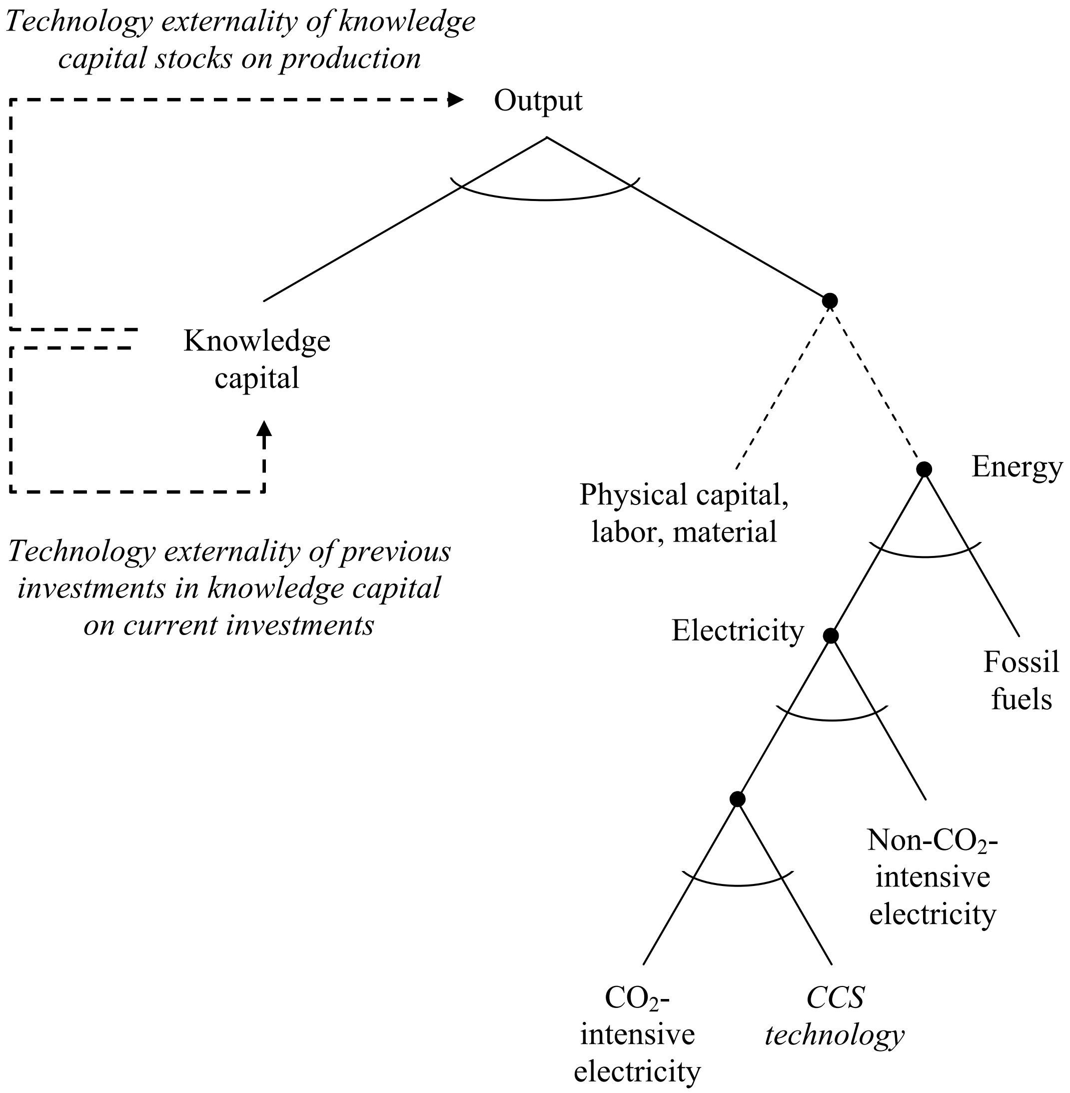
[1] There exist more types of technology externalities (see for an overview e.g. Jaffe et al., 2002). For simplicity, however, we restrict ourselves to a specification of the two types discussed above.

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 representative producers. When income is balanced and markets clear at all points in time as well, the output, price and income paths constitute an equilibrium.

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.

Figure 1 Structure of production and specification of technical change



3. Model calibration

Computable general equilibrium models that build on input-output tables as part of the national accounts have difficulties accounting for knowledge since national input-output tables extended with satellite accounts on R&D activities are typically not available. However, investment data for knowledge capital that is consistent with the national accounting framework is available for the Netherlands and in the following we show how we account for knowledge capital based on current attempts to integrate R&D indicators into the system of national accounts (SNA). We then lay out the central parameter values and data used in the model. Finally, we describe the calibration of the CCS technology.

3.1. Knowledge capital accounting

Knowledge capital accounting requires the identification and capitalization of flows associated with knowledge and subsequent incorporation of these in the national accounting matrix (Statistics Netherlands, 2000). The UN expert group on the measurement and treatment of non-financial assets focuses on the recording of R&D and intangible capital.[2] We take a broader perspective on knowledge and identify expenditures on R&D as well as investments in information- and communication infrastructure (ICT) as knowledge flows. ICT is included because of its role in disseminating and storing knowledge. ICT is therefore an important part of the infrastructure required for knowledge to be productive (Haan and Rooijen-Horsten, 2004).

A subsequent step involves the capitalization of selected knowledge flows such that we can record services derived from the knowledge stocks in separate arrays in the national accounting matrix. We capitalize knowledge flows into a single stock. An additional (column) account then registers investments in the stock of knowledge capital whereas an additional (row) account registers the derived services in the national accounting matrix. Investment in ICT is reported as investment and expenditures on R&D are reported as derived services. Regarding the capitalization itself, we use the perpetual inventory method, which is the most commonly used method to measure capital stocks and is in line with e.g. the Frascati manual (OECD, 2002). A key parameter in the perpetual inventory method is the depreciation rate, for which additional information is required. We assume the Dutch economy to be on a balanced growth path in 1999, which implies a fixed relation between investments in and services

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[2] This group is better known as the Canberra II Group and is formed as part of the process of updating the 1993 System of National Accounts (SNA93).

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 two knowledge flows.

To avoid double counting of the knowledge flows, we debit selected entries of the national accounting matrix. This debiting is straightforward for expenditures on ICT: since investments in ICT are originally reported as investments in physical capital, we debit the investment (column) account with the amounts of investment in ICT. However, debiting is less straightforward for expenditures on R&D as the intermediate goods matrix of the national accounting matrix needs to be debited. In this case, an assumption needs to be made as to which entries of the intermediate goods matrix to debit. One can either assume that R&D leads mostly to knowledge that is not necessarily embodied in intermediate inputs or that R&D does lead mostly to embodied knowledge.[3] If we assume that knowledge is embodied in tangible goods and services the intermediate goods matrix can be debited in a straightforward manner proportionally to the intermediate input shares in total output of the sectors (see Terleckyj, 1974). The former assumption, however, necessitates the additional step of creating an interindustry technology matrix to debit the intermediate goods matrix proportionally to the number of patents that a sector manufactures and uses (Scherer, 1982). Since the superiority of the patent data is not immediately clear and its availability is patchy for non-industrial sectors such as services, we follow Terleckyj (1974) and use intermediate input shares for our purposes. We balance the national accounting matrix by adjusting the (row) account for labor. Table 2 presents the resulting national accounting matrix for the Netherlands in 1999.

Table 2 National accounting matrix with knowledge accounting for the Netherlands in 1999 (billion euro)

	AGR	CII	SER	TT	NRG	CIE	NCIE	EX	C	I	R	S	Total
AGR	16.8	0.1	0.1	2.3	0.0		<0.1	28.2	7.4	0.7	1.0	0.1	56.7
CII	0.9	5.9	1.8	11.1	0.2	0.1	0.1	33.2	4.0	0.3	4.9	<0.1	62.3
SER	0.6	0.8	4.1	5.6	0.3	<0.1	<0.1	79.9	7.1	0.5	1.2	<0.1	100.5
TT	4.4	5.9	18.8	103.1	1.3	0.7	0.1	30.8	160.9	89.4	22.3	0.2	437.8
NRG	1.0	1.3	2.0	2.1	4.5	0.9		9.9	5.4	0.1	0.8	0.1	28.0
CIE&NCIE	0.6	0.8	0.7	1.3	0.1	3.4	0.5	1.2	2.2	<0.1	0.4		11.1
Imports	14.3	21.0	13.8	60.3	6.2	1.3			62.9	23.6		0.3	203.6
Net taxes	-0.7	0.1	-1.0	4.2	4.6	0.4	<0.1						7.7
Labor	6.0	10.9	33.2	133.5	1.3	0.8	0.1						185.8
K	11.7	10.1	25.5	89.1	8.7	2.2	0.3	0.6	17.0	3.5			168.6
H	1.1	5.4	1.4	24.8	0.8	0.4	<0.1						33.9
Total	56.7	62.3	100.5	437.8	28.0	10.0	1.1	183.7	266.8	118.0	30.5	0.5	

with EX = Exports, C = Consumption, I = Investment physical capital, R = Investment knowledge capital, S = Supply changes, K = Services from physical capital, H = Services from knowledge capital

Source: Statistics Netherlands (2000), Haan and Rooijen-Horsten (2004), and own calculations

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[3] See van Pottelsberghe de la Potterie (1997) for a more detailed discussion of both assumptions.

3.2. Elasticities and other parameters

We use the Dutch national accounting matrix for 1999 to calibrate the parameters of the functional forms from a given set of quantities, prices and elasticities. We base our choice of elasticities on reviews of the relevant literature (see Table 3). The assumed 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). We obtain the substitution elasticities in production from the TaxInc model (Statistics Netherlands, 1990). We use the substitution elasticity between knowledge capital and remaining inputs from Goulder and Schneider (1999). The substitution elasticity in aggregate electricity production is assumed. We assume a 5 percent depreciation rate of physical capital δ^K and a 25 percent depreciation rate for knowledge capital δ^H. Regarding the latter depreciation rate, 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 lifespans of applied R&D expenditures, which suggests an average service life of four to five years. In addition, we assume a coefficient value for the technology externality in innovation ξ 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., 2006a, who find a positive feedback effect of 45 percent with delays up till eight years). We base the coefficient value for the technology externality in production γ 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. We use techno-economic data for key electricity supply technologies to divide the electricity sector into CO_2-intensive and non-CO_2-intensive electricity generation. We obtain data on fossil-fuel inputs in the Netherlands from the GTAP-EG database (Paltsev and Rutherford, 2000) and matched with CO_2 emission data for the Netherlands (Koch et al., 2002). We assume an interest rate of 5 percent. We introduce a R&D subsidy on investments in knowledge capital in both the CO_2 intensive and non-CO_2 intensive electricity sectors to correct (partly) for technology externalities in the electricity sector. This assumed R&D policy makes the climate policy more effective by supporting the development on new electricity technologies in all simulations. We set the subsidy at 50 percent which is in line with Otto et al. (2006b). We consider a 42-year time horizon, defined over the years 1999 through 2040, and calibrate the model to a balanced growth path of 2 percent. Table A.5 summarizes the parameter values.

Table 3 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							4.0
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		AGR	CII	SER	TT	NRG	CIE	NCIE
σ^{H}	Between knowledge capital & rest	1.0	1.0	1.0	1.0	1.0	1.0	1.0
σ_i^{KLEM}	Between intermediate inputs & rest	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	0.3	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	

3.3. Calibration of the CCS technology

Electricity generation technologies fired by natural gas and coal are being used for respectively base- and mid-load electricity demand in the Netherlands. Table 4 shows the expected costs of these electricity generation technologies with CCS in the Netherlands.[4]

The generation costs are based on a natural-gas combined cycle and include cost estimates for CO_2 capture, but not storage. 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, electricity generated by the natural-gas combined cycle with CCS is 8 percent more expensive than the cost of conventional electricity. This estimate corresponds 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 the CCS technology cannot be stated with certainty.

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[4] A more detailed comparison of the various CCS technology options for the Netherlands can be found in Damen et al. (2006).

Neither do we know its full potential with precision. We assume that all CO_2 captured in the Netherlands can also be stored and that adoption can be immediate once the CCS technology becomes commercially available. Nevertheless, it is expected that further technical change will bring down costs or increase its potential or both over time.

Table 4 Cost of electricity with CO_2 capture and storage in the Netherlands (€ct/kWh)

	Without CCS	With CCS
Electricity generation and CO_2 capture		
Capital		1.5
Fuel		3.0
Operation and maintenance		0.5
CO_2 storage		0.2
Transmission and distribution		2.9
Total	7.5	8.1
Markup (percent)	0	8
CO_2 capture rate (percent)	0	85

Notes: The CCS technology is based on a natural gas combined cycle, which is the predominant electricity technology in the Netherlands. 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.

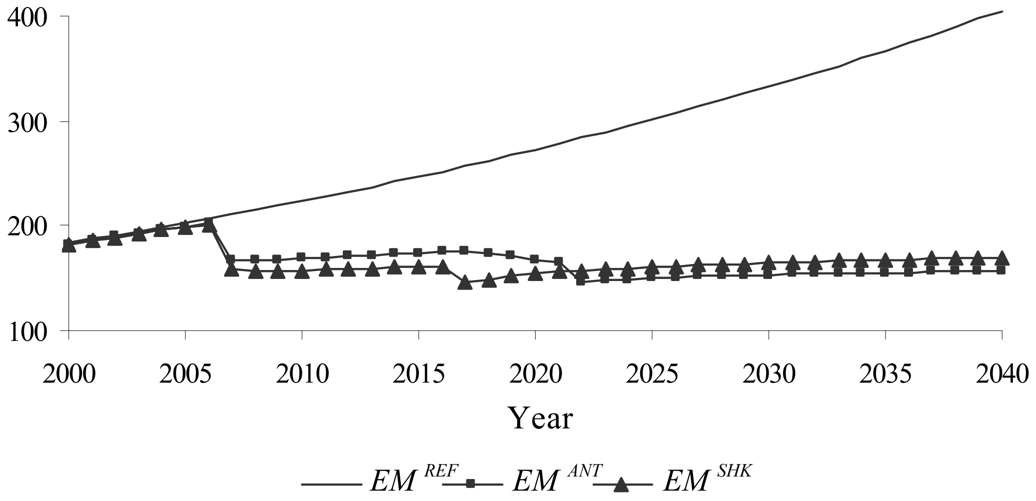
4. Simulation results

Our simulations refer to climate policy in the form of CO_2 emissions trading schemes which achieve a 40 percent reduction in cumulative emissions relative to the reference case, approximating stabilization of CO_2 emissions at 6 percent below 1990 levels for the Netherlands, as agreed upon in the Kyoto protocol. This assumes the stabilized level would also apply in post-Kyoto commitment periods (i.e. after 2012) to the end of the model horizon. The CO_2 trading schemes are differentiated between the CO_2 intensive and non-CO_2 intensive sectors. To avoid leakage of CO_2 emissions to consumption in all simulations, we also abate these emissions using a separate, but otherwise identical quantity constraint. We introduce the policies from 2007 onward and conduct a gridded search across the parameter space of the CO_2 emissions trading schemes to find their cost effective differentiation between CO_2 intensive and non-CO_2 intensive sectors.

We distinguish two alternative climate policy simulations with respect to the anticipation of a competitive and radical CO_2 abatement technology. The first simulation *ANT* refers to the case in which competitiveness and commercial availability of the CCS technology is anticipated. The second simulation *SHK* refers to the case in which competitiveness of the CCS technology is not anticipated and its commercial availability constitutes a technology shock. To later ensure comparability of the utility results between both simulations, we partition the model for simulation *SHK* into one version for the period before adoption and another version for the period after adoption. The exact timing of adoption is taken from simulation *ANT* and this timing determines the periods of the partitioned model versions for simulation *SHK*. The *SHK* model version before adoption is calibrated to the regular starting values in 1999, but without the CCS technology being available. The *SHK* model version after adoption, however, is calibrated to the equilibrium values of the previous reference equilibrium at the time of adoption, but now with the CCS technology being competitive and commercially available. As the CCS technology is not available in the version before adoption and the version after adoption is only specified from the time of adoption onward, the CCS technology cannot be anticipated in advance.

In both simulations, the CCS technology enters endogenously in the year 2017. Figure 2 illustrates the aggregate CO_2 emissions in the reference case and in both simulations. The typical abatement pattern consists of relatively less abatement in early years and more abatement in later years. In simulation *ANT*, agents know about the availability of the cheap abatement option in the future and postpone reduction efforts. In simulation *SHK*, the agents do not know about the availability of the cheap abatement option in the future and initially reduce their emissions more compared to simulation *ANT*. Because of the higher emission reductions in the first period, however, emission reductions in simulation *SHK* are lower than in simulation *ANT* in the second period after the technology shock. On hindsight, the climate policy has been too stringent in the first period in simulation *SHK* and can now be relaxed somewhat in the second period.

Figure 2 Aggregate CO_2 emissions in both simulations (Mt CO_2)



CO_2 shadow prices correspond to these abatement profiles (see Table 5). In the first period before the CCS technology becomes competitive, shadow prices are higher in simulation *SHK*. In the second period, however, they no longer are necessarily higher. Furthermore, shadow prices are relatively higher in CO_2-intensive sectors in both simulations. In principle, cost effectiveness of climate policy requires equalization of marginal abatement costs across sectors and therefore uniform price instruments. Yet, if there are technology externalities such as knowledge spillovers or learning, it has been shown that it becomes more cost effective to differentiate the climate policy according to the relative difference in technology externalities between sectors (see e.g. Otto et al., 2006b). Specifically, two effects related to technology externalities determine the equilibrium differentiation. On the one hand, technology externalities have a negative effect on abatement costs and hence provide an incentive to differentiate climate policy to sectors with a relatively high level of technology externalities (abatement cost effect). On the other hand, technology externalities have a positive effect on productivity and output levels and hence provide an incentive to differentiate climate policy to sectors with a relatively low level of technology externalities (opportunity cost effect). Given our model specification, the opportunity cost effect is strong relative to the abatement cost effect and we find it cheaper to shift some abatement toward CO_2-intensive technologies (with relatively low technology externalities) and sectors in both simulations.

Table 5 Effects of the directed climate policy on CO_2 shadow prices

Simulation	Shadow prices (€/t CO_2)	
	CO_2 intensive	Non-CO_2 intensive
Reference	0.0	0.0
ANT - Competitiveness of the CCS technology is anticipated	11.8	1.7
SHK - Competitiveness of the CCS technology is unanticipated		
Before adoption	15.3	10.1
After adoption	8.5	6.7

Table 6 summarizes the implications of the two simulations for intertemporal utility measured in terms of Hicksian equivalent variation. Stringent climate policy induces in both simulations a costly reallocation of resources towards less CO_2-intensive production and consumption and hence leads to adverse welfare effects. This is true even with technology externalities, which damp the negative effects of CO_2 constraints (see Otto et al., 2006b). Intertemporal utility, however, is slightly higher if competitiveness of the CCS technology is unanticipated. In the first partitioned model of simulation *SHK,* in which the CCS technology has not yet been adopted, the CO_2 constraint is more stringent than in simulation *ANT*. Compared to this simulation, one does not wait with abatement and sit it out till the CCS technology becomes competitive in simulation *SHK*. That is, the higher CO_2 shadow prices direct technical change to non-CO_2 intensive sectors and hence lead to higher investments in knowledge capital and their welfare-enhancing technology externalities in these sectors in the first period relative to the *ANT* simulation. Non-CO_2 intensive industries and services are the sectors to which most technical change is directed. Path dependency ensures that technical change remains directed more to these sectors in the second period in the *SHK* simulation, resulting in relatively higher overall investments in knowledge capital in this simulation. Yet, if the CCS technology is not competitive over the whole model horizon the climate policy leads to a welfare loss of 2.26 percent. The mere existence of a competitive CCS technology thus substantially lowers the welfare costs in our simulations. The degree of anticipation has only smaller effects on discounted utility. Not anticipating the CCS technology lowers the welfare cost of the climate policy with 0.20 percent from 1.71 to 1.51 percent. This result expands the findings of Popp (2006) for a model with a backstop technology and induced technical change provided via research and development (ENTICE-BR), who finds that the biggest savings in the costs of climate policies come not from induced technical change, but from simply adding a backstop to the model.

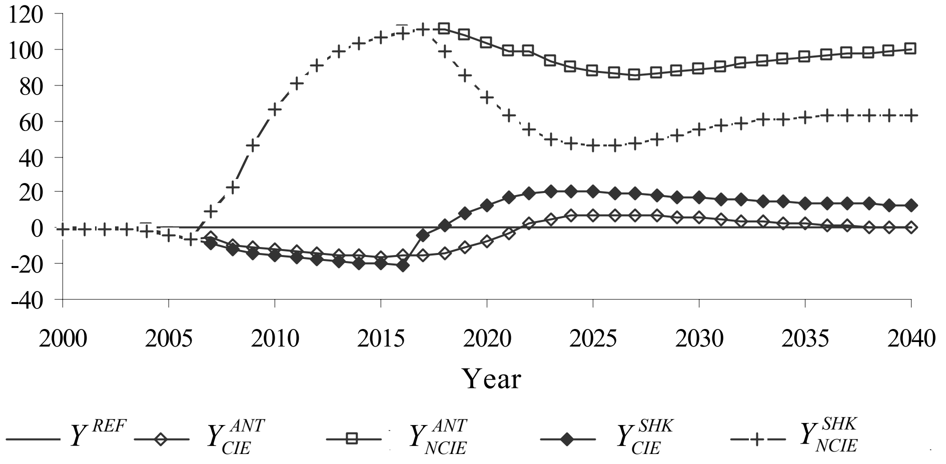
Table 6 Effects of the directed climate policy on intertemporal utility

Simulation	Discounted welfare	Year of Adoption
Reference	0.00 %	No
Hypothetical reference - CCS technology is not competitive	-2.26 %	No
ANT - Competitiveness of the CCS technology is anticipated	-1.71 %	2017
SHK - Competitiveness of the CCS technology is unanticipated	-1.51 %	2017

Note: We express intertemporal utility in percentage changes relative to the reference case.

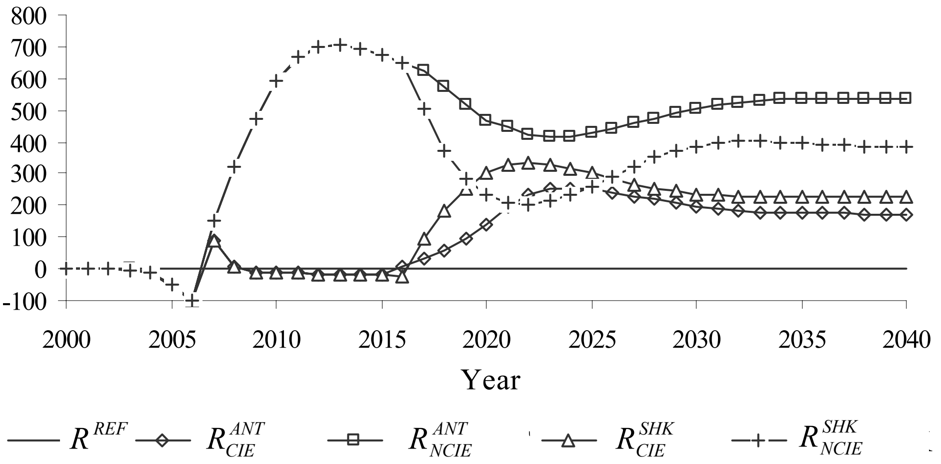
Figure 3 illustrates the impacts of the differentiated CO_2 constraints on electricity production in both simulations. In general, the CO_2 constraints lead to decreased levels of electricity generation in the CO_2-intensive electricity sector and increased levels in the non-CO_2 intensive electricity sector. This is especially true in the years before the CCS technology is adopted. Once the CCS technology becomes competitive, however, large quantities of electricity can be generated with few CO_2 emissions in the CO_2-intensive sector and this sector now gains market share in the electricity market to the extent that CO_2-intensive electricity generation even increases relative to the reference case for many years. This result is more pronounced in simulation *SHK* than in simulation *ANT* as CO_2 shadow prices are more exacerbated in the former simulation than in the latter. The CO_2-intensive electricity sector, for example, faces a higher shadow price in simulation *SHK* than in simulation *ANT* in the first period. As a result, it is cost effective for this sector to reduce electricity generation relatively more in simulation *SHK* in the first period. Likewise, the CO_2-intensive sector faces a relatively low CO_2 shadow price in the second period and finds it then cost effective to increase its electricity generation relatively more in simulation *SHK*. To a certain extent, this increased electricity generation in the CO_2-intensive sector comes at the cost of electricity generation in the non-CO_2 intensive sector, which now loses even more market share compared to simulation *ANT*. The market share of CO_2-intensive electricity decreases from 90 percent in the reference case to 79 percent of total electricity generation in simulation *ANT* whereas the market share decreases to merely 86 percent in simulation *SHK*.

Figure 3 Electricity generation in both simulations (in percentage change vs. reference case)



Finally, impacts of the differentiated CO_2 constraints on the direction of technical change are similar to the impacts on sectoral production as more knowledge capital is required for a sector to expand and less knowledge capital is required for a sector to contract (see Figure 4). Because of the dynamic nature of the technical change process, however, the impacts are more pronounced compared to impacts on electricity generation.

Figure 4 Investments in knowledge capital in both simulations (in percentage change vs. reference case)

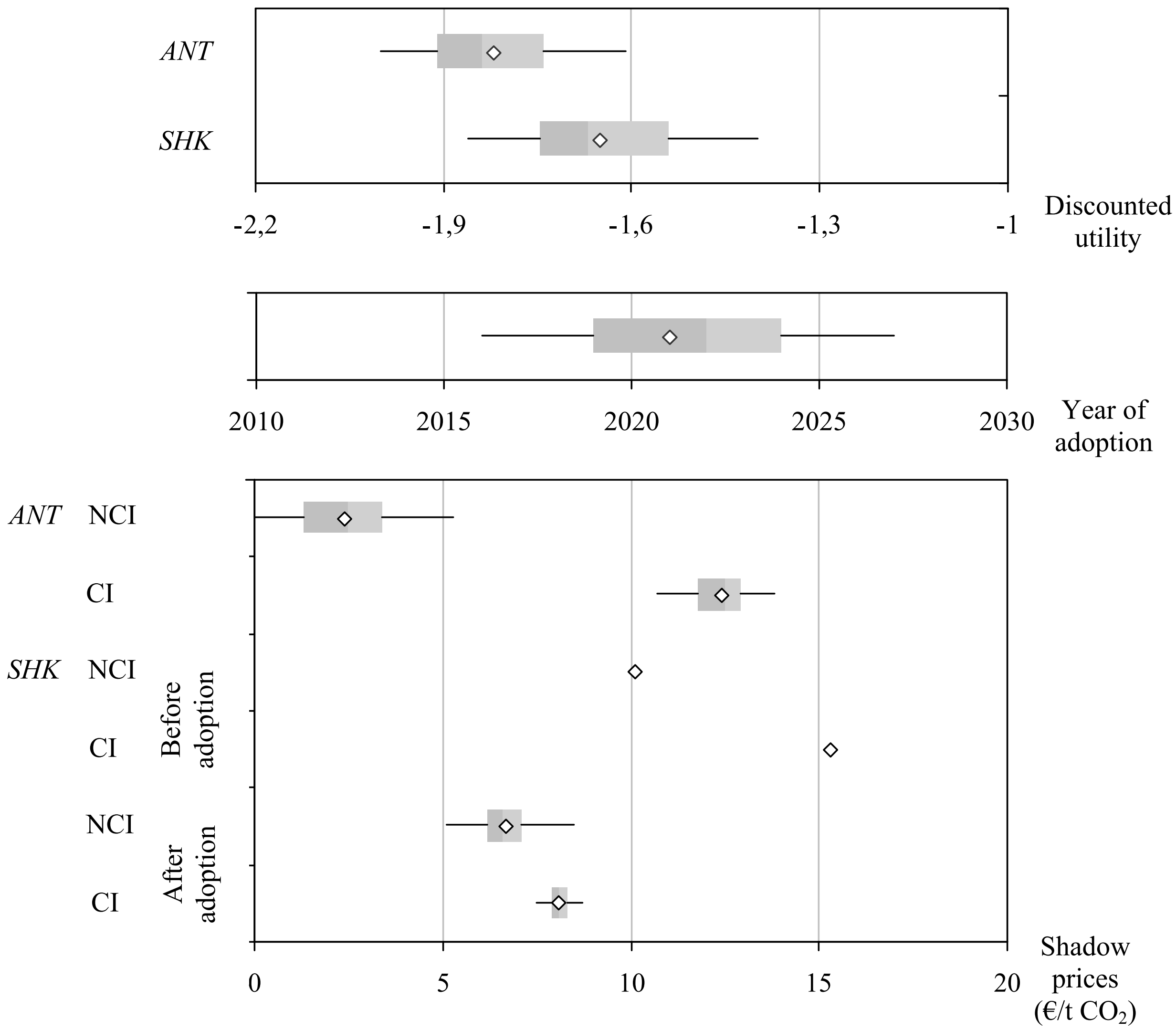


5. Uncertainty analysis

Assumptions about the cost and performance of the CCS technology are uncertain. To account for these parameter uncertainties, we perform an uncertainty analysis that aims at quantifying the overall uncertainty associated with our model outputs. For the uncertainty propagation we apply a simple Monte Carlo method. It involves the random sampling from the distribution of inputs and successive runs of the original model. We use central parameter values in all Monte Carlo simulations except for the parameters subject to analysis. Specifically, we analyze both the cost markup over the cost of conventional electricity and the CO_2 capture rate, thus addressing uncertainties of the (cost) potential of the CCS technology. Since we have only information on the range of possible values for these parameters, but no information about which values are more likely to occur, we draw from a uniform distribution. The markup ranges between 7 and 15 percent and the capture rate between 85 and 95 percent. These statistics are in line with recent survey studies (Damen and al., 2006; IPCC, 2005). The simple Monte Carlo method requires a substantial number of model runs to obtain a good approximation of the output distribution. We recomputed the output with 1000 samples.

The results of the uncertainty propagation are presented in Figure 5. The simple box plots provide statistics for intertemporal utility, entry of the CCS technology and CO_2 shadow prices. The plots consist of a box drawn with its left and right edges at the 25th percentile and 75th percentile (hinges). Whiskers extend from each hinge to its respective minimum and maximum. Different colours within the box indicate the median and a diamond shows the mean. Although we observe some spread, all of our insights based on the central case estimates of cost and performance of the CCS technology remain robust even when we account for uncertainty in the CCS parameterization. In all Monte Carlo runs intertemporal utility is higher if competitiveness of the CCS technology is unanticipated. The range (interquartile range) for the discounted utility is, however, significant and amounts to almost 0.4 percent points (0.2 percent points) in simulation *ANT* and *SHK*. The interquartile range for the endogenous entry of the CCS technology encompasses years from 2019 to 2024. The CO_2 shadow prices are relatively higher in CO_2-intensive sectors in simulation *ANT* and *SHK* in all samples. Shadow prices are higher before adoption of the CCS technology in simulation *SHK*. However, the shift of abatement burden toward CO_2-intensive technologies is diminished in all Monte Carlo runs in the second period.

Figure 5 Results of Monte Carlo simulation



5. Conclusions

We have studied the implications of unanticipated technical change for the design of climate policy in a dynamic general equilibrium model for the Netherlands that explicitly captures empirical links between CO_2 emissions associated with energy use, directed technical change and the economy. We compared a simulation in which competitiveness of the CCS technology is anticipated with a simulation in which the competitiveness is not anticipated.

Based on simulations with our model, we summarize the key insights as follows: (*i*) The typical abatement pattern consists of relatively less abatement in early years and more abatement in later years. However, agents reduce more emissions initially with a technology shock. The relatively too stringent climate policy is then relaxed after the CCS technology shock. The CO_2 shadow prices correspond to these abatement profiles. Due to the technology externality, cost effective climate policies are differentiated according to the difference in technology externalities between non-CO_2 intensive and CO_2-intensive sectors and some abatement is shifted toward CO_2-intensive technologies and sectors; (*ii*) Stringent climate policy leads to adverse welfare effects, but intertemporal utility is slightly higher if competitiveness of the CCS technology is unanticipated. In this case, higher CO_2 shadow prices lead to both higher investments in knowledge capital and their welfare-enhancing technology externalities; (*iii*) The CO_2 constraints lead to decreased levels of electricity generation in the CO_2-intensive electricity sector and increased levels in the non-CO_2 intensive electricity sector. Once the CCS technology becomes competitive, however, CO_2-intensive electricity generation even increases relative to the reference case for many years. This result is more pronounced in the simulation in which competitiveness of the CCS technology is not anticipated. (*iv*) The propagation of uncertainties regarding the (cost) potential of the CCS technology confirms the robustness of our qualitative findings. The quantitative impacts of directed climate policy on intertemporal utility, however, vary considerably with the assumed CCS cost markup and the CO_2 capture rate.

We would like to make some remarks on the representation of the CCS technology in our framework. Our integration of the CCS technology is in a way that Sue Wing (2006) referred to as semi-endogenous because the (endogenous) timing of the backstop's penetration is determined by the technology parameters, which are inevitably exogenous. The parameters are based in large part on engineering judgment and few recent deployments of the CCS technology. The cost and performance of large-scale applications of this technology are still uncertain and have been taken into account in our Monte Carlo analysis. However, we have seen that the welfare difference between our two simulations is relatively small compared to the case where no CCS technology at all is available. This might shift the focus of future analysis to the competitiveness of the backstop technology. We have so far not considered the link between R&D investments and costs of the backstop carbon-free technology. A first step in this direction is the work by Bosetti and Tavoni (2007) in a different model set-up.

Two main conclusions might be drawn from our analysis. First, anticipating a technology like the CCS technology leads to reduced R&D investments and postponed emission reductions efforts awaiting the silver bullet technology on the horizon in the energy sector. However, this is not only environmentally dangerous, but also not advisable from an economic perspective. Diversifying the investment portfolio - besides spreading the risks that some technologies might fail - leads to lower welfare costs of climate policy because of the technological externalities associated with investments in knowledge capital. Second, the CCS technology option shows the political economic limitations in designing a differentiated climate policy instrument. With the CCS technology deployment, the dirty sectors become much cleaner which blurs the traditional delineation of environmental policy along the lines of CO_2 intensity. Climate policy has to be flexible to take into account these technological developments.

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Appendix A Structure 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:

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

where:

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

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

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

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

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

Production of electricity with the CCS technology:

$$\Pi_{i,t}^{Y} \equiv \overline{H}_{i,t}^{-\gamma}\ CES\left(r_{i,t}^{H}, p_{i,t}^{KLEM}; \sigma^{H}\right) - p_{i,t} \geq 0 \qquad \perp Y_{i,t} \qquad i = CIE\,;\ t = 1,..,T \qquad \text{(A.2)}$$

where:

$$p_{i,t}^{KLEM} = LT\left(r_t^{K}, w_t, p_{j,t}, p_{CI}^{EM}, p_t^{EL}, p_{i,t}^{A}\right) \qquad j = NRG$$

Aggregate production of electricity:

$$\Pi_t^{EL} \equiv CES\left(p_{i,t}; \sigma^{EL}\right) - p_t^{EL} \geq 0 \qquad \perp EL_t \qquad i \in EL\,;\ t = 1,..,T \qquad \text{(A.3)}$$

Investments in knowledge capital:

$$\Pi_{i,t}^{R} \equiv \overline{R}_{i,t-1}^{-\zeta}\ p_{i,t} - p_{i,t+1}^{H} = 0 \qquad \perp R_{i,t} \qquad i \notin EL\,; t = 1,..,T-1 \qquad \text{(A.4)}$$

$$\Pi_{i,t}^{R} \equiv \overline{R}_{i,t-1}^{-\zeta}\ p_{i,t} - (1-s)p_{i,t+1}^{H} = 0 \qquad \perp R_{i,t} \qquad i \in EL\,; t = 1,..,T-1$$

$$\Pi_{i,T}^{R} \equiv \overline{R}_{i,T-1}^{-\zeta}\ p_{i,T} - p_i^{TH} = 0 \qquad \perp R_{i,T} \qquad i \notin EL$$

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

Stock of knowledge capital:

$$p_{i,t}^{H} = r_{i,t}^{H} + \left(1-\delta^{H}\right) p_{i,t+1}^{H} \qquad \perp H_{i,t} \qquad i = 1,..,I\,;\ t = 1,..,T-1 \qquad \text{(A.5)}$$

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

Investments in physical capital:

$$\Pi_t^{I} \equiv CD\left(p_{i,t}, CES\left(r_t^{K}, p_t^{FDI}; \sigma^{A}\right)\right) - p_{t+1}^{K} = 0 \qquad \perp I_t \qquad t = 1,..,T-1 \qquad \text{(A.6)}$$

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

Stock of physical capital:

$$p_t^K = r_t^K + \left(1-\delta^K\right) p_{t+1}^K \qquad \perp K_t \qquad t=1,..,T-1 \tag{A.7}$$

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

Armington aggregate:

$$\Pi_{i,t}^A \equiv CES\left(p_{i,t}^{IM}, CES\left(p_{j,t};\sigma_i^M\right);\sigma^A\right) - p_{i,t}^A \geq 0 \qquad \perp A_{i,t} \qquad \begin{cases} i=1,..,I; \, j \notin E; \\ t=1,..,T \end{cases} \tag{A.8}$$

Imports of goods:

$$\Pi_{i,t}^{IM^Y} \equiv p_t^{FX} - p_t^{IM} \geq 0 \qquad \perp IM_{i,t}^Y \qquad i=1,..,I \, ; \; t=1,..,T \tag{A.9}$$

Imports of coal:

$$\prod_t^{IM^{COAL}} \equiv p_t^{FX} - p_t^{COAL} \geq 0 \qquad \perp IM_t^{COAL} \qquad t=1,..,T \tag{A.10}$$

Foreign direct investment:

$$\Pi_t^{FDI} \equiv p_t^{FX} - p_t^{FDI} \geq 0 \qquad \perp FDI_t \qquad t=1,..,T \tag{A.11}$$

Exports of goods:

$$\Pi_t^{EX^Y} \equiv CD\left(p_t^{EL}, p_{i,t}\right) - p_t^{FX} \geq 0 \qquad \perp EX_t^Y \qquad i \notin EL \, ; \; t=1,..,T \tag{A.12}$$

Exports of physical capital:

$$\Pi_t^{EX^K} \equiv r_t^K - p_t^{FX} \geq 0 \qquad \perp EX_t^K \qquad t=1,..,T \tag{A.13}$$

Intratemporal utility:

$$\Pi_t^W \equiv CES\left(p_t^{FX}, CES\left(p_{j,t}, p_t^E;\sigma_W^{YE}\right);\sigma^A\right) - p_t^W \geq 0 \quad \perp W_t \qquad j \notin E \, ; \; t=1,..,T \tag{A.14}$$

where:

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

Intertemporal utility:

$$\Pi^U \equiv CES\left(p_t^W;\rho\right) - p^U = 0 \qquad \perp U \tag{A.15}$$

A.2. Market clearing conditions

Goods:

$$\begin{aligned} Y_{j,t} = {} & \frac{\partial \Pi^{R}_{i,t}}{\partial p_{j,t}} R_{j,t} + \frac{\partial \Pi^{I}_{t}}{\partial p_{j,t}} I_{t} + \sum_{i} \frac{\partial \Pi^{A}_{i,t}}{\partial p_{j,t}} A_{i,t} \\ & + \frac{\partial \Pi^{W}_{t}}{\partial p_{j,t}} W_{t} + \frac{\partial \Pi^{EX^{Y}}_{t}}{\partial p_{j,t}} EX^{Y}_{t} \end{aligned} \qquad \perp p_{j,t} \qquad j \notin E \, ; \; t = 1,..,T \tag{A.16}$$

$$\begin{aligned} Y_{j,t} = {} & \frac{\partial \Pi^{R}_{i,t}}{\partial p_{j,t}} R_{j,t} + \frac{\partial \Pi^{I}_{t}}{\partial p_{j,t}} I_{t} + \sum_{i} \frac{\partial \Pi^{Y}_{i,t}}{\partial p_{j,t}} Y_{i,t} \\ & + \frac{\partial \Pi^{W}_{t}}{\partial p_{j,t}} W_{t} + \frac{\partial \Pi^{EX^{Y}}_{t}}{\partial p_{j,t}} EX^{Y}_{t} \end{aligned} \qquad \perp p_{j,t} \qquad j = NRG \, ; \; t = 1,..,T$$

$$Y_{j,t} = \frac{\partial \Pi^{R}_{i,t}}{\partial p_{j,t}} R_{j,t} + \frac{\partial \Pi^{I}_{t}}{\partial p_{j,t}} I_{t} + \frac{\partial \Pi^{EL}_{t}}{\partial p_{j,t}} EL_{t} \qquad \perp p_{j,t} \qquad j \in EL \, ; \; t = 1,..,T$$

Electricity:

$$EL_{t} = \sum_{i} \frac{\partial \Pi^{Y}_{i,t}}{\partial p^{EL}_{t}} Y_{i,t} + \frac{\partial \Pi^{EX^{Y}}_{t}}{\partial p^{EL}_{t}} EX^{Y}_{t} + \frac{\partial \Pi^{W}_{t}}{\partial p^{EL}_{t}} W_{t} \qquad \perp p^{EL}_{t} \qquad t = 1,..,T \tag{A.17}$$

Knowledge capital (in market):

$$\frac{r^{H}_{i,t} H_{i,t}}{r + \delta^{H}} = \frac{\partial \Pi^{Y}_{i,t}}{\partial r^{H}_{i,t}} Y_{i,t} \qquad \perp r^{H}_{i,t} \qquad i = 1,..,I \, ; \; t = 1,..,T \tag{A.18}$$

Knowledge capital (in stock):

$$H_{i,t=1} = H_{0i} \qquad \perp p^{H}_{i,t=1} \qquad i = 1,..,I \tag{A.19}$$

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

$$TH_{i} = \left(1 - \delta^{H}\right) H_{i,T} + R_{i,T} \qquad \perp p^{TH}_{i} \qquad i = 1,..,I$$

Physical capital (in market):

$$\frac{r^{K}_{t} K_{t}}{r + \delta^{K}} = \frac{\partial \Pi^{I}_{t}}{\partial r^{K}_{t}} I_{t} + \sum_{i} \frac{\partial \Pi^{Y}_{i,t}}{\partial r^{K}_{t}} Y_{i,t} + \frac{\partial \Pi^{EX^{K}}_{t}}{\partial r^{K}_{t}} EX^{K}_{t} \qquad \perp r^{K}_{t} \qquad t = 1,..,T \tag{A.20}$$

Physical capital (in stock):

$$K_{t=1} = K_0 \qquad \perp\ p_{t=1}^{K} \qquad \text{(A.21)}$$

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

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

Labor:

$$L_t = \sum_i \frac{\partial \Pi_{i,t}^{Y}}{\partial w_t} Y_{i,t} \qquad \perp\ w_t \qquad t = 1,..,T \qquad \text{(A.22)}$$

Coal (imports):

$$IM_t^{COAL} = \sum_i \frac{\partial \Pi_{i,t}^{Y}}{\partial p_t^{COAL}} Y_{i,t} \qquad \perp\ p_t^{COAL} \qquad t = 1,..,T \qquad \text{(A.23)}$$

Import aggregate:

$$IM_{i,t}^{Y} = \frac{\partial \Pi_{i,t}^{A}}{\partial p_{i,t}^{IM}} A_{i,t} \qquad \perp\ p_{i,t}^{IM} \qquad i = 1,..,I\ ;\ t = 1,..,T \qquad \text{(A.24)}$$

Armington aggregate:

$$A_{i,t} = \frac{\partial \Pi_{i,t}^{Y}}{\partial p_{i,t}^{A}} Y_{i,t} \qquad \perp\ p_{i,t}^{A} \qquad i = 1,..,I\ ;\ t = 1,..,T \qquad \text{(A.25)}$$

Foreign investments:

$$FDI_t = \sum_i \frac{\partial \Pi_t^{I}}{\partial p_t^{FDI}} I_t \qquad \perp\ p_t^{FDI} \qquad t = 1,..,T \qquad \text{(A.26)}$$

Foreign exchange:

$$\begin{aligned} BOP_t = {} & \frac{\partial \Pi_t^{EX^Y}}{\partial p_t^{FX}} EX_t^Y + \frac{\partial \Pi_t^{EX^K}}{\partial p_t^{FX}} EX_t^K - \sum_i \frac{\partial \Pi_{i,t}^{IM^Y}}{\partial p_t^{FX}} IM_{i,t}^Y \\ & - \frac{\partial \Pi_t^{IM^{COAL}}}{\partial p_t^{FX}} IM_t^{COAL} - \frac{\partial \Pi_t^{FDI}}{\partial p_t^{FX}} FDI_t - \frac{\partial \Pi_t^{W}}{\partial p_t^{FX}} W_t \end{aligned} \qquad \perp\ p_t^{FX} \qquad t = 1,..,T \qquad \text{(A.27)}$$

CO$_2$ emissions in consumption:

$$EM_W = \sum_t \frac{\partial \Pi_t^{W}}{\partial p_W^{EM}} W_t \qquad \perp\ p_W^{EM} \qquad \text{(A.28)}$$

CO_2 emissions in production:

$$EM_c = \sum_i \sum_t \frac{\partial \Pi^Y_{i,t}}{\partial p^{EM}_c} Y_{i,t} \qquad \perp p^{EM}_c \qquad c = CI, NCI \tag{A.29}$$

Intratemporal utility:

$$W_t = \frac{\partial \Pi^U}{\partial p^W_t} U \qquad \perp p^W_t \qquad t = 1,..,T \tag{A.30}$$

Intertemporal utility:

$$U = \frac{B}{p^U} \qquad \perp p^U \tag{A.31}$$

A.3. Income balance

$$\begin{aligned} B = {} & \sum_i \left(H_{i,0} - p^{TH}_i TH_i\right) + K_0 - p^{TK} TK + \sum_t w_t L_t + \sum_c p^{EM}_c EM_c \\ & - \sum_{i=EL} \sum_{t=9}^{T} s \frac{\partial \Pi^R_{i,t}}{\partial p_{i,t}} R_{i,t} + \sum_t p^{FX}_t BOP_t \end{aligned} \tag{A.32}$$

A.4. Endowments

Supply of labor:

$$L_t = \left(1+g\right)^{t-1} L_0 \qquad t = 1,..,T \tag{A.33}$$

Balance of Payments:

$$BOP_t = \left(1+g\right)^{t-1} BOP_0 \qquad t = 1,..,T \tag{A.34}$$

A.5. Constraints

CO_2 emission constraint of climate policy in consumption:

$$EM_W = \left(1-a\right) \sum_t \left(1+g\right)^{t-1} EM_{0W} \tag{A.35}$$

CO_2 emission constraint of climate policy in production:

$$EM_c = \left(1-a^c\right) \sum_t \left(1+g\right)^{t-1} EM_{0c} \qquad c = CI, NCI \tag{A.36}$$

where:

$$a\ EM = \sum_{c} EM_c$$

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 knowledge 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*
$\overline{H}_{i,t}$	Technology externality applied in production 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*
$\overline{R}_{i,t}$	Technology externality in innovation 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
r_{t}	Rental rate of capital at time *t*
w_{t}	Wage rate at time *t*

Table A.5 Parameters

Description		Value
s	R&D subsidy	0.500
a	CO_2 emissions reduction	0.400
γ	Coefficient of technology externality in production	0.090
ξ	Coefficient of technology externality in innovation	0.200
g	Growth rate	0.015
r	Interest rate	0.050
δ^K	Depreciation rate of physical capital	0.050
δ^H	Depreciation rate of knowledge capital	0.250