8. RESPONSES TO TECHNOLOGY AND TAXES IN A SIMULATED WORLD

Abstract A set of model experiments was performed to analyze the role of technology development on energy system responses to a uniform global carbon tax. Stabilization at a carbon dioxide concentration of 550 ppmv from the IMAGE 2.2 B2 baseline was shown to be technically feasible at limited cost based on a combination of improved energy efficiency, fuel switching and in the longer introduction of carbon-free options. Technology development under baseline conditions, induced technology development by climate policies and technology inertia (based on their lifetimes) are identified as important factors in explaining the different responses under different conditions. For example, technology development, modeled as learning by doing, increases the global carbon reduction in 2030 from nearly 40 to 60% as a result of a 300 US$/tC tax. The relative importance of the three factors mentioned plays a major role in the optimal timing of abatement efforts. For long-term responses not only has technology development been shown to be important, but also other dynamic processes in the energy system, such as depletion, which can sometimes work in the opposite direction.

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8.1 Introduction

According to the IPCC assessment report, climate change observed over the 20th century was mostly caused by human activities (IPCC, 2007). As further global warming is likely to result in increasing risks of negative impacts on both natural systems and human societies around the world, significant reductions of greenhouse gas emissions may be needed. IPCC reports also indicate that technologies for significantly reducing current emissions with respect to baseline development in the next 20 years are already available (IPCC, 2001). However, reducing emissions on a large enough scale to prevent significant climate change using current technologies is seen in a number of studies to be costly. For this reason, development of better technologies will, certainly in the long term, need to play an important role in providing a pathway to further reduce emissions at reasonable costs.

Several tools are used to study pathways to less greenhouse gas-intensive futures and the role which might be taken by different (types of) technologies within these pathways: see, for instance, IPCC's Third Assessment Report (Metz et al., 2001) for an overview., The focus on the role of technology development has significantly increased in the last few years. Several concepts of technology development and its driving forces have been explored, including (descriptions of) autonomous improvement, R&D-driven improvement and improvement driven by use ("learning-by-doing"). The last category, in particular, has received considerable attention from modelers, both thanks to its empirical basis and the means provided to endogenize technological progress in models (see e.g. Grübler et al., 1999; Wene, 2000). Understanding the processes that determine technology development, and related to this, the potential of different technological options, is very important for developing mitigation strategies, both in terms of their costs and their timing.

In this chapter, we will focus on the role of technology development within different mitigation scenarios and its possible consequences for mitigation costs, for example. More specifically, we will search for relevant dynamics within the system that could be important for the role that technological development may play, both in the long and medium terms. Such dynamics include, for instance, the relationship with capital turnover rates (and inertia in the system), technology development already included in the baseline scenario, development induced by climate policies (both based on learning curves) and the influence of resource depletion. The relative contribution of these different processes is crucial in the debate on the timing of mitigation action.

The analysis was done with the TIMER 1.0 model, part of the integrated assessment model IMAGE 2.2 (see Chapter 2). The model was developed to study the long-term dynamics of the energy system, in particular, transitions to systems with low carbon emissions (de Vries et al., 2001; IMAGE-team, 2001). TIMER is a system-dynamic energy system model at a medium level of aggregation. The model uses learning curves for almost all its technologies. The position of TIMER within the integrated assessment framework of IMAGE also allows us to study not only such factors as environmental impacts and co-benefits – but also land-use consequences of mitigation choices. Earlier, the model was used to explore pathways to reach a stabilization of the atmospheric concentration of CO_2 at 450 ppmv from the B1 scenario (van Vuuren and de Vries, 2001). In this chapter, we continue this type of analysis by looking at different mitigation scenarios that will bring the carbon concentration to 500-600 ppmv by the end of the century, starting from the B2 baseline scenario[i].

We will first address several methodological issues, including some of the relevant processes of technological change in relation to climate policies, and the most relevant features of TIMER. Secondly, we will briefly describe how the B2 baseline scenario is implemented in TIMER, providing the context for our further analysis. Thirdly, we will look at the results of the various mitigation experiments explored. These are divided into three experiments. The first investigates how stabilization of greenhouse gas concentrations can be achieved starting from the B2 scenario. The second experiment looks into some of the relevant dynamics of long-term mitigation scenarios (until 2100). The last experiment looks in detail at the different processes relevant for medium-term energy-system response to mitigation action. The last section deals with the main conclusions.

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[i] Both the B1 and B2 baseline scenarios are part of total set of 6 IPCC scenarios introduced in the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000). B2 is a medium emission scenario in the total set. The scenario will be discussed in more detail later.

8.2 Theoretical background and methodology

The IMAGE 2.2 integrated assessment model and its energy system model, TIMER, used in the analysis, will be overviewed later in this section. First, we discuss some of the dynamic processes of particular importance for the influence of technology development (assuming the use of learning curves) on the response of the energy system to mitigation action. The modeling experiments are outlined at the end of the section.

8.2.1 Dynamic processes that influence technological development

The main focus here is the role of technology development on the costs of emission reductions in the medium and long term. The term technology development refers to changes in the portfolio of technologies used to supply energy to end-users. In stricter sense it refers to changes to the set of available technologies that change (improve) their performance either in terms of utility or costs. A method to explore the influence of technology development in an energy model is to analyze the response of the model to externally applied carbon tax. Several authors have used such a method, in which taxes are progressively increased, to develop so-called marginal-abatement cost curves (Ellerman and Decaux, 1998; Criqui et al., 1999)[ii]. This concept functions as a main element in our analysis – defining system response R, as indicated in equation (8.1). Here, E_{tax} represents the emissions after a tax has been applied and $E_{baseline}$ the emissions in the case of a baseline.

$$R = E_{tax} / E_{baseline} \tag{8.1}$$

The focus in this chapter is on changes in the system response R as a result of technological change at the global level. The use of an energy-system model allows us to study these responses in the context of the (full) dynamics in the world energy system, including depletion and trade but also several technology-relevant processes. In fact, we recognize six dominant dynamic processes in models that are directly related to technological development – and directly influence the response of the model to external impulses. These are:

- switches between different technologies as a result of changes in relative costs;
- technology development under baseline conditions;
- induced technology development in response to a carbon tax;
- technology inertia as result of limited capital turnover rates;
- investments in research and development;
- impacts of technology-specific resource depletion.

[ii] The curves can be interpreted as marginal-abatement cost curves where the carbon tax is seen as an indicator of mitigation costs. A more general term for these curves is “system-response” curves.

We will discuss these processes in the context of the modeling experiments explored, indicating their importance for the total system response. Here, these processes are only briefly introduced:

- *Switches between different technologies as a result of changes in relative costs.* The most direct impact of a carbon tax is that it changes the relative costs of fuels/technologies and thus also their penetration. This leads to additional use of zero/low carbon fuels/technologies.
- *The influence of the technology progress already included in the baseline scenario.* In general, costs of new renewable (zero-carbon) technologies such as solar/wind and biomass will, under the baseline, decrease more rapidly than the costs of more mature, fossil-based technologies (in a model, this process can be formulated in terms of learning-by-doing if niche markets exist or alternatively by exogenous assumptions). As a result, the gap that climate policies need to bridge over time in enforcing the penetration of the more expensive zero carbon options (compared to the cheaper fossil options) decreases. A consequence of this, all other factors being equal, is that later introduction of a tax will lead to a stronger response (in terms of equation 8.1) than if the same tax had been introduced earlier.
- *The influence of technology progress induced by climate policies.* The learning-by-doing mechanism (see also section 8.2.3) implies that further employment of renewable technologies in response to a carbon tax will cause further cost reductions of these technologies. These technologies would then become more attractive, and thus, all other factors being equal, the response to a carbon tax would slowly increase over time.
- *The influence of technology inertia.* There is much inertia in the energy system. As capital is normally only replaced at the end of its lifetime, a response to a carbon tax can only slowly penetrate into the system. The response of some energy demand sectors can be somewhat swifter than in other sectors as technical lifetimes of the technologies used are shorter than in energy production. Futhermore, to some degree, behavioral changes and so-called good housekeeping measures may allow for almost immediate responses. Thus, as a result of inertia alone, the response to a carbon tax will slowly increase over time.
- *Investment in research and development.* Another important process that could stimulate technology development is investing in research and development (R&D). There is some discussion whether this process can be seen as a separate process for technology development (“learning-by-searching”), or whether it should be seen in conjunction with learning-by-doing (Grübler et al., 1999). If seen as a separate process, investments into R&D can bring down costs of more expensive low-carbon options without applying these technologies first, increasing the response to a carbon tax in time.
- *The influence of resource depletion.* Indirectly, the use of a carbon tax also changes the resource depletion dynamics of different forms of energy (e.g. depletion of fossil fuel resources, higher production costs of renewable energy as less suitable sites are used etc.). Important in this context is that different fuels/technologies have their own depletion characteristics.

These different processes are strongly related to the earlier discussion on the timing of mitigation action. The second process (learning at the baseline) leads to the conclusion that it is better to wait for technologies to develop before implementing strict climate policies. This argument was forcefully presented in Wigley et al. (1996) in their discussion on timing of mitigation action. In contrast, the third process enforces the argument that climate policies should be seen as a lever with which to bring about climate-friendly technical innovation and diffusion, favoring an early-action type of approach (Azar and Dowlatabadi, 1999; Wene, 2000; van Vuuren and de Vries, 2001). The fourth process translates into an argument that climate policy should not result in premature replacement of capital. This argument was used by Wigley et al (1996) as a reason for later abatement being cheaper. However, others have argued that after including fully all system inertia, this argument actually gives preference to early action to make the transition as smooth as possible (Grubb, 1997; Ha-Duong et al., 1997). The fifth process might, in turn, favor a strategy in which first strong investments into R&D are made, followed later by large-scale employment of available technologies (once they have become competitive). Finally, the influence of the sixth process is ambiguous. A crucial issue arising from a final decision on timing is how important these processes are in relation to each other.

In an earlier publication, we looked into how the total set of processes could be worked out in a scenario with very positive assumptions about technology development and low energy use (the SRES B1 scenario) (van Vuuren and de Vries, 2001). We found early action to be a more favorable strategy than delayed response for a discount rate of 4% and lower, as postponing measures foregoes the benefits of learning-by-doing. Using higher discount rates would favor a delayed response approach. Here, we intend to analyze the underlying technology dynamics in greater detail, and relate the outcomes to the discussion on timing of climate policy as described above.

8.2.2 Modeling framework

We used the TIMER 1.0 energy system model and the integrated assessment framework IMAGE 2.2[iii].

IMAGE 2.2

IMAGE 2.2 was developed to assess the impact of global environmental problems, in particular, climate change (IMAGE-team, 2001). IMAGE consists of a set of linked and integrated models collectively describing the chain of global environmental change from population and economic change to impacts on ecosystems and agricultural systems. The models operate on two geographical scales. Most of the drivers and socio-economic processes (population, economy, agricultural demand, energy use, emissions) are calculated for 17 world regions. In addition, a large number of the environmental parameters are calculated at the grid level of 0.5 x 0.5 degrees. The IMAGE 2.2

[iii] An abbreviation of Integrated Model to Assess the Global Environment

scenarios cover the 1970-2100 period. In 2001, the model was used to re-implement the IPCC SRES scenarios (base year updated to 1995) (IMAGE-team, 2001).

TIMER 1.0

TIMER 1.0 is an energy-system model describing the supply and demand of 12 different energy carriers for 17 world regions. A description of the model is given in Chapter 2 of this thesis, while a full description of TIMER 1.0 can be found in De Vries et al. (2001). The main objective of the TIMER model is to analyze the long-term trends in energy demand and efficiency and the possible transition towards renewable sources. The model focuses particularly on several dynamic relationships within the energy system, such as inertia, learning-by-doing, depletion and trade among the different regions. This makes the model very suitable for studying some of the long-term dynamics related to technology development discussed in section 8.2.1.

The energy demand submodel of TIMER determines demand for fuels and electricity in five sectors (industry, transport, residential, services and other) based on structural change, autonomous and price-induced change in energy intensity (“energy conservation”) and price-based fuel substitution. The demand for electricity is fulfilled by fossil-fuel based thermal power, hydro power and two other non-thermal alternatives, i.e. nuclear power and solar/wind. The option “solar/wind” describes a renewable electricity option with characteristics of both solar and wind power. Both nuclear power and solar/wind penetrate the market based on relative costs. The thermal power option consists of four alternative options: coal-based, oil-based, natural-gas based and biomass-based, all of which are fully intercompetitive. The exploration and exploitation of fossil fuels (either for electricity or direct fuel use) are described in terms of depletion and technological development. Biofuels can be used in place of fossil fuels, and are, in turn, also assumed to be subject to technological development and resource depletion dynamics. Below we will describe the processes in TIMER that relate directly to the dynamic processes discussed in section 8.2.1. More detailed on these processes are given in Chapter 2.

Technology development

An important aspect of the TIMER model is the endogenous formulation of technological development on the basis of “learning-by-doing”. This phenomenon has been investigated in detail, and for a variety of products and processes. The concept also received great interest as a meaningful representation of technological change in global energy models (Azar and Dowlatabadi, 1999; Grübler et al., 1999; Wene, 2000). A general formulation is that a cost measure tends to decline as a power function of an accumulated learning measure:

$$y = \alpha^{*}\, Q^{-\pi} \tag{8.2}$$

where π is the learning rate, Q, the cumulative output and α, a constant. Often, the learning rate, π, is expressed by the progress ratio ρ, which indicates how fast the costs measure, y, decreases with the doubling of experience, Q. It is easy to see that $\rho=2^{-\pi}$.

Many illustrations of this law have been found and published. The progress ratio in almost all cases investigated was found to be between 0.65 and 0.95, with a median value of 0.82 (Argotte and Epple, 1990). In Chapter 2, the dynamics of the "learning-by-doing" formulation are illustrated for some hypothetical examples.

In the TIMER model, "learning-by-doing" influences the costs of coal, oil and gas production, the investments of renewable and nuclear energy, and the decline of the energy conservation cost curves. The value of the progress ratio (ρ) varies from 0.7 to 1.0, based on historic ρ values for the different technologies. The choice of these values will depend on the technologies and scenario-setting. First of all, the progress ratios of solar/wind and biomass have been set lower than those for fossil-based technologies founded on observed historic trends (Wene, 2000). There is evidence that in the early stages of development, ρ values for learning-by-doing curves are lower (thus faster learning) than for technologies that have already been in use for long periods (see also Chapter 2). In TIMER all ρ values are time-dependent, with ρ values rising to 0.9 or higher before 2100 for all technologies. The development of the learning rates is also related to the storyline of the scenario. Table 8.1 gives the ρ values used in the B2 scenario of TIMER.

An interesting question is whether learning curves should be applied at the level of regions or for the world as a whole. On the one hand, technologies developed in one region will, in most cases, also be available in other regions. On the other hand, a significant portion of cost reductions are actually representative of the experience gained by applying the technology. In TIMER, the learning curves are applied at the level of separate regions; however, to model the influence of technology transfer, we assume that all other regions will benefit partly from the additional knowledge gain of the forerunner (de Vries et al., 2001).

Depletion

The role of depletion varies according to the technology/energy carrier. Depletion is described in terms of long-term supply curves (related to cumulative production) for the fossil-fuel technologies and nuclear energy (see Chapter 2 for a discussion of these curves for different technologies). The curves used in TIMER 1.0 are derived from Rogner (1997) and the World Energy Assessment (Goldemberg, 2000). Contrarily, for

Table 8.1 Progress ratios used in the B2 scenario as implemented in TIMER

Technology	*Progress ratio 1995*	*Progress ratio 2100*
Coal production	0.90-0.94	0.95-0.96
Oil production	0.85	0.92
Natural gas prod.	0.86-0.93	0.90
Efficiency	0.85-0.9	0.92
Nuclear	1.00	0.96
Solar/wind	0.80	0.90
Biomass	0.88	0.92

Note: The trajectory for values between 1995 and 2100 is linear.

renewable sources, depletion is described as a function of production. This formulation assumes that less attractive sites or technologies will have to be used at higher production levels. Specific investment costs and the maximum production levels for renewable energy have been derived from various sources, as indicated in the model documentation (de Vries et al., 2001). These derived values include, in particular, the resource estimates of the World Energy Assessment and calculations made using the IMAGE 2.2 land-use model (Goldemberg, 2000; Hoogwijk, 2004). A specific form of “depletion” is found in the electricity sector – where it is assumed that only a limited share of solar and wind power can be adopted free of charge– after which additional investments need to be made into the system to assure sufficient reliability (e.g. storage or grid extensions). These additional costs are assumed to come into play where the share of solar/wind in total electricity production is above 20%[iv].

Substitution between different technologies

Substitution among energy carriers and technologies is described in the model with the multinomial logit model (Edmonds and Reilly, 1985):

$$IMS_i = \exp(-\lambda^* c_i) / \sum_j \exp(-\lambda^* c_j) \tag{8.3}$$

IMS_i is the indicated share in total investments of production method, i, λ, the so-called logit parameter determining the sensitivity of markets to relative prices and c_i, the cost or the price of production method, i. The last factor may include other factors such as those related to premium, additional investment costs and cost increases as result of a carbon tax. The multinomial logit model implies that the share of a certain technology (or fuel type) depends on its costs relative to its competitors. The cheapest option gains the largest market share. However, it does not get the full market share, since the formulation assumes heterogeneity within the market, creating specific niches for technologies with higher average costs (but lower costs than its alternatives within this specific niche). The multinomial logit mechanism is used within TIMER to describe substitution among end-use energy carriers, different forms of electricity generation (coal, oil, natural gas, solar/wind and nuclear) and substitution between fossil fuels and biofuels. It should be noted that the mechanism is actually used to determine shares in new investment only, which implies that actual market shares respond much slower. Again, Chapter 2 illustrates the dynamics of this formulation for hypothetical examples.

8.2.3 Modeling experiments

In order to learn more about the possible role of different technology pathways, we performed three different model experiments, starting from IMAGE implementation of the SRES B2 scenario, i.e.:

[iv] As can be seen in Chapter 2, the modeling of the power sector has been heavily updated in TIMER 2.0. Instead of one factor capturing additional costs, processes that may lead to increased costs are now modeled independently (declining capacity credit, mismatch between supply and demand and spinning reserve).

a) A scenario aimed at stabilization of atmospheric carbon dioxide concentration at 550 ppmv (around 2150);
b) A series of three model runs in which a 100 US$/tC carbon tax is introduced: i) going immediately from zero to 100 US$/tC between 2000 and 2010; ii) increasing at 25US$/tC per decade in the first 40 years after 2000 – and staying constant at 100 US$/tC after 2040, and iii) increasing at 10 US$/tC per decade for the whole 2000-2100 period (see Figure 8.4).
c) A series of model runs in which different levels of carbon taxes are applied in 2000, 2010, 2020 and 2030, with the response recorded 10-30 years later.

In the first experiment, we looked at the types of technologies chosen by the model to achieve the required level of mitigation. Attention is also paid to the emission reductions of other greenhouse gases and impacts on energy-exporting regions. The emission profile leading to the 550 level is based on the so-called WRE profiles (Wigley et al., 1996). In the second set of experiments, a carbon tax was introduced in three different modeling runs, in all cases reaching a level of 100 US$/tC (see Figure 8.4); however, the rates of introduction varied among the different experiments. The aim of this experiment was to find out whether technology dynamics within the system would result in different responses to these taxes in the long term. Specifically, one might expect the run reaching the final 100 US$/tC tax level early in the simulation to benefit more from the induced technology development than any of the other runs. The last set of experiments took place in a much shorter time frame. It also searched specifically for the different contributions to the overall system in its response to a carbon tax of induced technological learning, where learning forms part of the baseline and inertia.

It is important to note that the model applied in this study does not take into account physical carbon sequestration (removing carbon from the energy system for underground/underwater storage) or options to reduce land-use related emissions.

8.3 Baseline scenario

The IPCC SRES B2 scenario has been developed within a total set of six baseline scenarios, none of which includes explicit climate policies (Nakicenovic and Swart, 2000). The IPCC SRES scenarios are based on the development of narrative “storylines” and the quantification of these storylines using six different integrated models from different countries. For each scenario, the elaboration by one specific model has been chosen as being characteristic for that particular storyline, the so-called “marker scenario”. Elaboration of the same storyline by other models needs to fulfill certain criteria in order to qualify as a fully harmonized scenario. The B2 storyline describes a regionalized world with a focus on environmental and social values, but in reality for most of implementation of this scenario a “dynamics-as-usual” interpretation is chosen (Riahi and Roehrl, 2000). The IMAGE 2.2 implementation, in contrast, has put slightly more emphasis on the original storyline thus resulting in somewhat lower emissions than the marker (IMAGE-team, 2001). The IMAGE 2.2 B2 scenario can still be regarded as

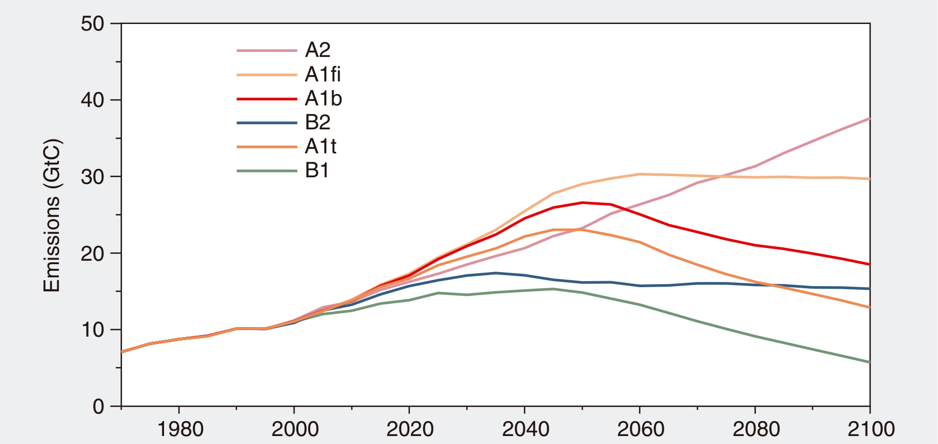

Figure 8.1 Global greenhouse gas emissions in the IMAGE 2.2 implementation of the SRES scenarios (all Kyoto gases and all sources) (IMAGE-team, 2001).

a medium emission scenario, with global greenhouse gas emissions increasing from 10 GtC-eq. in 2000 to around 15 GtC-eq. in 2100 (see Figure 8.1) (In comparison with the total literature, this can be regarded as a medium emission scenario - see Chapter 6). In terms of sectors, energy use remains the cause of the larger share of emissions. Driven by increasing emissions, the atmospheric carbon dioxide concentration in the B2 scenario increases from 370 ppmv to 605 ppmv in 2100 (or 425 ppmv CO_2-eq to 820 ppmv CO_2-eq), which is more than double pre-industrial levels. The global temperature increase is found in the range of almost three degrees above 1970 levels (using a climate sensitivity of 2.5°C).

8.4 Mitigation experiments

The results of the experiments described in section 8.2.3 are outlined below.

a) Stabilization at 550 ppmv

Reaching a profile that stabilizes the atmospheric carbon dioxide concentration at 550 ppmv from the IMAGE B2 scenario requires a reduction of cumulative emissions in the 2000-2100 period of about 25%. Such a reduction could be regarded as a relatively modest one[v]. If we introduce a uniform carbon tax (across regions and sectors) in TIMER, we need a tax slowly rising to 190 US$/tC to achieve such a reduction (no carbon tax is applied to land-use-related carbon emissions). The profile of the required carbon tax is shown in Figure 8.2.

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[v] The reduction is in size of the same magnitude as the reduction that is required for achieving stabilization at 450 ppmv of carbon dioxide in the atmosphere starting from the B1 baseline scenario that we described earlier (van Vuuren and de Vries, 2001). Further in this section we compare the results to those of the B1 450 ppmv analysis.

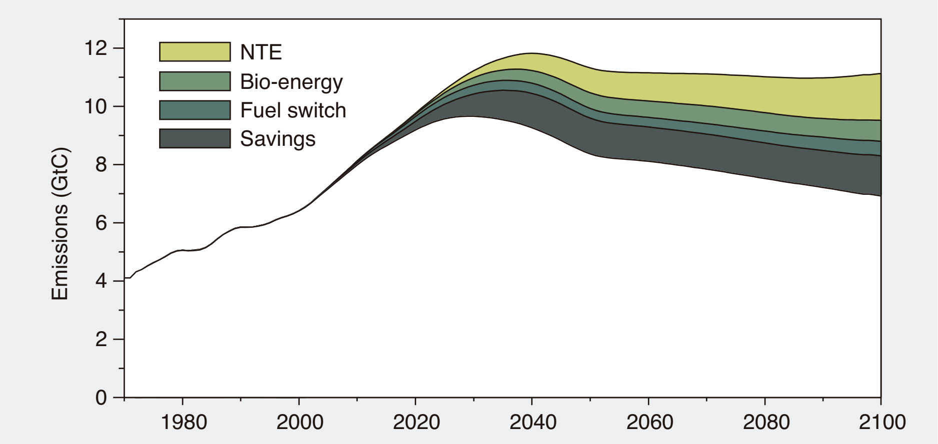

Figure 8.2 Allocation of carbon dioxide emission reduction from B2 to a 550 ppmv stabilization scenario.

In total, the required carbon tax reduces global primary energy use by about 10-15%. This decrease is unequally divided among the different energy carriers. Cumulative use of coal declines by almost 50%. The cumulative consumption of natural gas and oil declines by about 10% (the decline in natural gas is slightly higher than for oil, as natural gas experiences considerable competition from non-fossil energy carriers in the electricity market). Other, low/zero carbon, energy carriers gain a market share such as modern biomass (14% increase in cumulative consumption), and nuclear power and electricity from renewables (gain totals 36%).

In Figure 8.2, we attributed the reduction in carbon emissions from B2 to B2-550 to the different changes within the system[vi]. In the first two decades, the lion's share of the reductions come from energy efficiency improvement and the fuel switch from coal to other fossil fuels. By 2030, the other options start to become important: for example, use of biofuels instead of fossil fuels and non-thermal electricity modes (solar/wind and nuclear power) instead of fossil-based electricity[vii]. The largest reductions are likely to occur in the electrical power sector. This result can easily be understood if one looks at generation costs of the two fully competitive non-fossil power options compared to those of thermal power (Figure 8.3). In the baseline, from 2000 until around 2030 there is still a very clear gap between the generation costs of these options in favor of fossil-fuel based options; solar/wind still hovers around a factor that is 2-3 times more

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[vi] The actual size of each option depends somewhat on the order in which options are allocated. We first determined the total contribution from efficiency improvement, next from penetration of solar/wind and nuclear power and biofuels, then from biofuel penetration and finally for a fuel-switch among the different fossil fuels.

[vii] We have allowed additional use of nuclear power as a mitigation option in these calculations. In fact, as the cost of this option is lower in the baseline than the solar/wind power option, it represents the most attractive alternative in terms of a first response. The "learning" capacity of this option is, however, assumed to be lower than for solar/wind power. It should be noted that generation costs for fossil-based electricity is, in fact, calculated in the model through a weighted average of coal, oil and natural gas generation costs.

expensive, while the difference with nuclear power is somewhat smaller. In time, the costs of solar/wind power and nuclear power by learning-by-doing slowly decline, and around 2050 generation costs become nearly equal. As solar/wind power gain a considerable market share at that time, cost reductions start to be offset by lack of production sites – the best sites are already occupied. Besides this, the further penetration requires higher storage and/or distribution costs. As a result, fossil-fuel-based electricity remains the cheapest of the supply options in the baseline throughout the century. If a carbon tax is introduced into this system, it will easily shift the costs of the thermal options upwards (above the alternative costs for nuclear and solar/wind). This induces in the model a strong penetration of these options into the power generation system, allowing for sharp reductions of carbon dioxide emissions.

The strongest impact of the carbon tax is on coal use. Hence, the largest changes in terms of energy use will occur in regions with relatively high coal consumption and production rates. This includes China, India, South Africa and the USA. Impacts on oil use and trade are much smaller – in view of the relatively modest taxes required to reach 550 from the B2 scenario (also note that trade levels in B2 are somewhat lower than in other SRES scenarios). Middle East oil exports, for instance, decrease in terms of the ratio of export revenues to GDP from 11.6 to 11.1% in the 2000-2050 time period (Table 8.2). Impacts in regions with slightly higher production costs, such as the FSU, could be larger in relative terms. A number of other import regions could benefit from reduced oil imports around 2050, in particular, China and India.

Interestingly, changes in the trade of other fuels can paint a different picture for total energy exports as a percentage of GDP. The Former Soviet Union, for instance, suffers in the long-run (2030-2060) from reduced oil exports. The exploitation of this region's oil resources, very competitive by that time under the baseline, is subject to a carbon

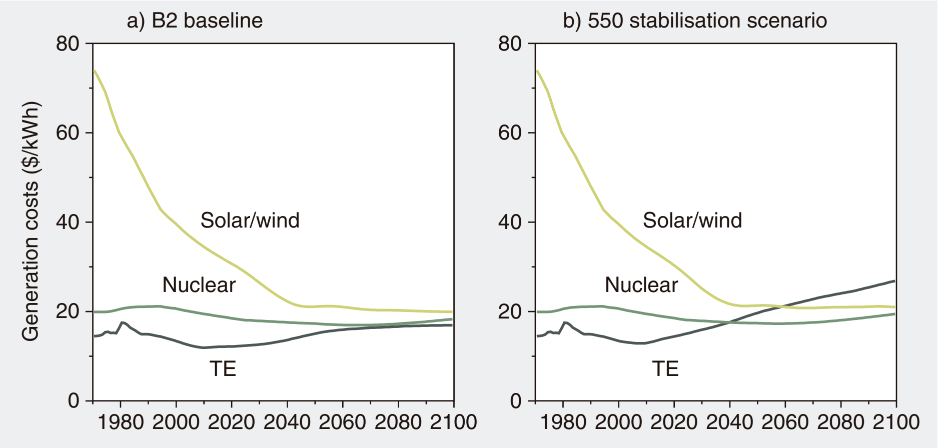

Figure 8.3 Generation costs of non-thermal options (solar/wind and nuclear) versus electricity from thermal-power plants (mostly fossil-fueled, but including biofuel, TE; electricity generation in the B2 baseline (left) and the 550 stabilization scenario (right).

Table 8.2 Volume of fuel trade as % of GDP in selected regions (2000-2050) (net imports negative; net exports positive)

	Oil export (% GDP)			*All energy export (% GDP)*		
	B2	B2-550	Diff.	B2	B2-550	Diff.
USA	-0.75	-0.71	*0.04*	-1.36	-1.41	*-0.04*
South America	1.09	1.02	*-0.07*	2.44	2.70	*0.26*
Western Europe	-0.57	-0.52	*0.05*	-1.14	-1.12	*0.02*
FSU	3.37	3.01	*-0.36*	10.44	10.97	*0.53*
Middle East	11.64	11.13	*-0.51*	13.58	13.11	*-0.47*
South Asia	-2.07	-1.93	*0.14*	-3.54	-3.53	*0.00*
East Asia	-0.70	0.67	*0.03*	-1.11	-1.22	*-0.11*
Japan	-0.66	-0.63	*0.03*	-1.28	-1.25	*0.03*

tax that by then will have reached a level of 50-100 US$/tC. In contrast, (2010-2030) this region benefits significantly in the medium term from increased natural gas exports to Western Europe and Japan. South America also sees some losses in oil exports – but these are offset as the region gains its experience in producing biofuels and becoming an important exporter of these fuels. Finally, for China, the reduction in oil exports is off set by an equally sharp increase in natural gas – and later biofuel imports (van Vuuren et al., 2003d).

The reduction of energy and industry-related carbon dioxide emissions amounts to about 25% in 2050 and 40% in 2100 (the latter being equal to 4.3 GtC/year). As a result of the induced changes in the energy system to the carbon tax (more energy crops to produce biofuels, thus less land for new forests), land-use emissions increase slightly by about 0.4 GtC. (a form of carbon leakage that could be reduced by additional policies oriented to land-use related emissions). The carbon tax does not directly tax non-carbon dioxide greenhouse gases either. However, as the carbon tax induces changes in the energy system, the emissions of other energy-related gases are reduced. For instance, energy-related methane emissions are reduced by about 10% compared to baseline (a 60% increase in emissions instead of a 70% increase), with corresponding advantages in terms of greenhouse gas concentrations. Sulfur emissions are also reduced by about 10% compared to baseline. The latter gives rise to important co-benefits of climate policies in terms of reduction of both urban and regional air pollution (van Vuuren et al., 2003a).

The B2-550 stabilization scenario developed here results in a rise in global average temperature of 2.6 °C vis-à-vis a temperature increase of 2.9 °C in the B2 baseline scenario. The gains from the reduction in the radiative forcing of carbon dioxide take place,, in particular, in the first decades, somewhat offset by a decrease in the negative forcing of sulfur aerosols.

If we compare the results for stabilizing the carbon concentration at 550 ppmv from the B2 scenario to our earlier analysis, we see that the required efforts and consequences are very comparable. Stabilizing the carbon concentration at 450 ppmv from the B1 scenario required a 200-230 US$/tC carbon tax by the end of the century (depending on the timing), versus the 190 US$/tC used here. Responses in terms of the contribution of different technologies also seems to be comparable – although reducing coal use is slightly more important in this B2-550 analysis in view of the higher shares of coal use in total energy use. In contrast, impacts on oil trade are smaller – most probably due to the more fragmented oil market in the B2 scenario.

Responses to different 100 US$/tC taxes

In the second set of experiments, a carbon tax is introduced that reaches a level of 100 US$/tC – but is introduced using three different rates.(see Figure 8.4).

Figure 8.5 shows that carbon dioxide emissions are reduced the fastest in the scenario that has already reached the 100 US$ level in 2010 (1), followed by the second and third scenarios. As a result, by 2100 the first scenario has a considerably lower carbon dioxide concentration than the third. We can also compare the relative reductions for the same tax levels. These are not always similar; apparently, model dynamics do play a role here. However, the expected effect (see section 8.2) of a sharper 2100 emission reduction in the first scenario compared to the others, due to a longer period of induced learning, is not visible. There are four important reasons inherent in the model for this:

- *Learning slows down with knowledge gained.* The learning curve describes technical progress as a function of the logarithm of cumulative production. This means that a similar improvement in production costs can be realized for each doubling of cumulative production, as explained in Section 8.2. Production itself cannot keep "doubling" its production rates throughout the century, thus cost reductions slow down in time. The scenario that reaches the 100 US$/tC as early as 2010 benefits from fast learning early in the scenario – but also experiences the consequences of slower learning afterwards.

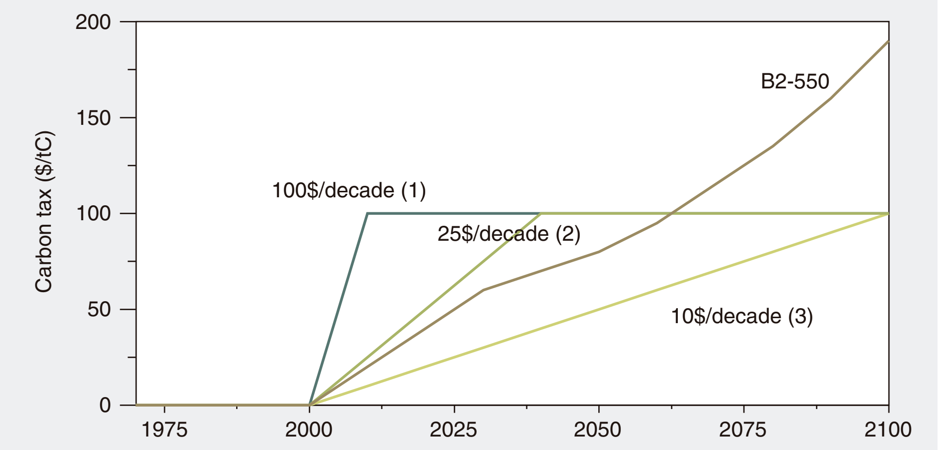

Figure 8.4 Overview of the taxes applied.

- *High production rates for renewables are costly.* We assume that depletion of renewable technology options are directly related to production rates (see section 8.2): high production rates imply that less favorable options (e.g. less favorable sites for wind power) have to be chosen. The early tax scenario results in higher production rates of these options – and thus experience higher depletion.
- *High shares of renewables induce costs.* Most of the renewable electricity options have a lower reliability than fossil-fuel options (i.e. due to the intermittent character of solar and wind power, renewable based capacity might not be able to generate power at the right moment). Therefore, total electricity production can only absorb a limited percentage of renewable electricity options (we assumed 20%) before requiring additional investments into the system to improve its reliability (e.g. storage or grid extensions that enlarge the system). This dynamic element has similar consequences to depletion described above.
- *Some cheap oil and gas are still available.* Finally, the competitive fossil-based alternatives will have slightly lower production costs in the first scenario than in the second and third scenarios as less depletion of cheap resources will have taken place.

In conclusion, in addition to "learning-by-doing" there are also other technology-relevant dynamic processes, some of which may work in the opposite direction to the expected gains for early action scenarios of "learning-by-doing". Under the B2 model assumptions in TIMER, these processes completely off set the gains of early action in terms of costs by 2100. On the other hand, it should be noted that the early action benefited from lower costs for solar/wind during most of the simulation (see Figure 8.6). Moreover, the environmental impacts of these three scenarios are certainly not similar (see carbon dioxide concentration in Figure 8.5).

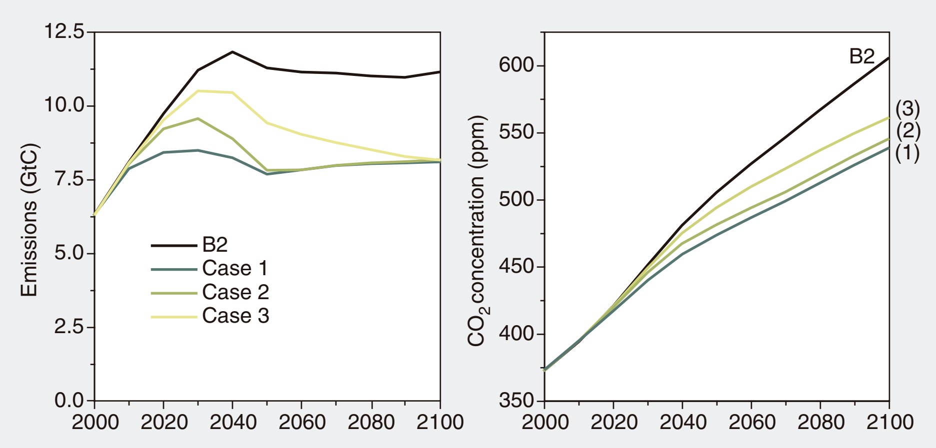

Figure 8.5 Global carbon dioxide emissions (left) and carbon dioxide concentration (right). Note: the numbers correspond to the different tax profiles of Figure 8.4.

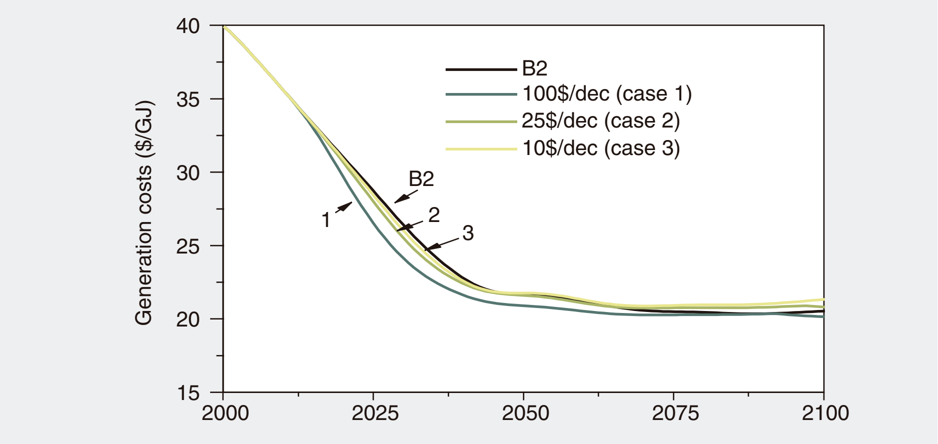

Figure 8.6 Costs of solar/wind power generation in TIMER.
Note: the numbers correspond to the different tax profiles of Figure 8.4.

c) Responses to carbon taxes with and without learning

In the last set of experiments, we took a shorter time horizon (2000-2030) and investigated whether we could identify the role of different relevant dynamics to determine the response to a carbon tax as defined in equation 8.1. We assumed that some of the dynamics discussed in the previous section were of less importance on this medium-term time scale, in particular those related to depletion. The three types of dynamics of particular importance for the medium-term response are technology development under baseline, induced technology development and system inertia.

We tried to get an idea of the influence of the three processes through a set of experiments in which we recorded the system response as a function of the year of introduction (t_{in}), the year in which we measure the system response (t_{rec}) and the level of the tax (T). For both t_{in} and t_{rec}, values were applied in five-year steps between 2000 and 2030. The level of the carbon tax varied between 0 and 600 US$/tC.

In the first experiment we focused on the recording year (t_{rec}). We introduced a carbon tax into the TIMER model in the year 2000 (t_{in}) of 10 US$/tC (T) and recorded its immediate impact in 2000, and its impact in 2010, 2020 and 2030 (t_{rec}) and after 10, 20 and 30 years, respectively. This experiment was repeated for the different tax levels between 10 and 600 US$/tC in steps of 10 US$/tC. This process is very similar to experiments in which modelers record the response of their model to carbon taxes in order to derive so-called Marginal Abatement Curves (MAC). However, in contrast to the normal MAC experiments, we looked at how the system response develops over time in the period after introduction of the carbon tax. Figure 8.7a shows the results of this experiment. The recordings have resulted in four system-response curves that indicate the reduction in global carbon emissions in four different years. All of the curves show the typical form of a MAC, in which the response increases along with the level of the tax but with decreasing additional gains. Figure 8.7a shows the response to the carbon

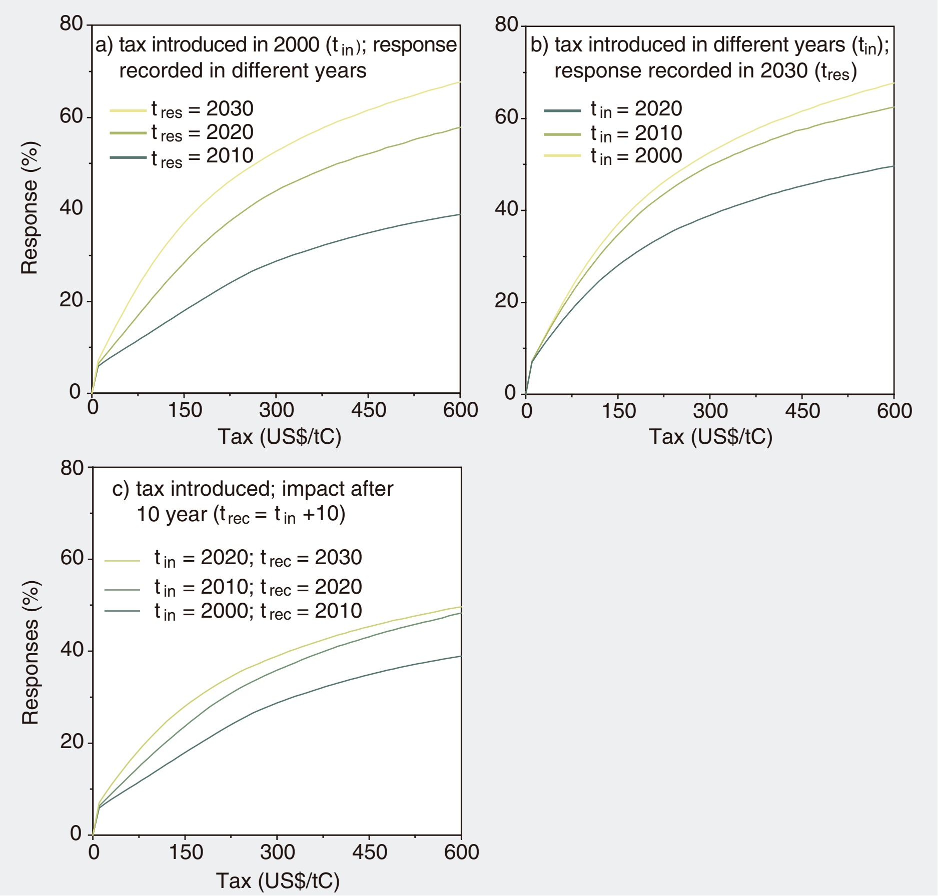

Figure 8.7 Response to a carbon tax: a. introduction year 2000 - different recording years; b. recording year 2030 - different introduction years and c. recording year 10 years after introduction year.

tax increasing with time. A 300 US$ tax introduced in 2000, for instance, has only a very limited response in 2000 itself but causes a 30% reduction of global carbon emissions after 10 years – and reduces global emissions by more than 50% after 30 years. “Baseline learning”, “induced learning” and “inertia” all contribute to this increasing response over time.

In a second experiment we brought in the time of introduction of the tax (t_{in}). What happens if the tax is not introduced in 2000, but in 2010 or 2020? We recorded the impact in 2030 (t_{rec}) of three different series of taxes introduced in 2000, 2010 and 2020, respectively (Figure 8.7b). The results are fairly similar to the previous experiment. A tax introduced in 2000 has the largest response, benefiting again from both baseline and induced learning processes, and having sufficient time to overcome the existing inertia. The 2030 response to a tax introduced in 2020 is significantly smaller. Interestingly, this curve lies some 10% above the curve in Figure 8.7a of the 2010 response of tax introduced in 2000 (both curves are included in Figure 8.7c). In terms of time elapsed after the tax was introduced, these cases are similar as both curves show the situation 10 years after the tax was introduced. Assuming that the role of inertia and induced learning will therefore be comparable, technology development under the baseline can be identified as an important process explaining these differences. Figure 8.7c shows all three curves, recorded 10 years after the introduction of the tax.

We continue this line of thinking, but now considering the introduction time t_{in} and the recording time t_{rec} as two independent axes in one graph. In this graph we show, for a given tax level T (in this case 300 US$/tC), all possible responses as a function of combinations of t_{in} and t_{rec}, in five-year steps. The surface that is created in this way obviously shows the strongest response in the lower right corner, as this depicts the situation of an early introduction of the tax (2000) and late recording (2030). The diagonal from the lower left corner (t_{in} = 2000, t_{rec} = 2000) to the right upper corner (t_{in} = 2030; t_{rec} = 2030) represents all points in which response is recorded immediately after the introduction of the tax – and responses along this diagonal are therefore small. All points going to the left upper corner from this diagonal are zero by definition (recording time before the introduction of the tax). This representation allows for a comparison in different directions. Horizontal and vertical lines through the graph show the influence of changes in recording time and introduction time, respectively, while diagonals compare cases with a constant time between t_{in} and t_{rec}. The highlighted diagonal in the graph, for instance, shows all cases with a 20-year time period between introduction of the tax and recordings for the 2020-2030 period.

We will first look at the results of this graph in the normal model mode (Figure 8.8; left upper graph). A 300 US$/tC tax gives a maximum response of almost 60% reduction of global CO_2 emissions if introduced in 2000 and recorded in 2030 (lower right corner). An important observation is that the graph is not symmetrical in its response to the two different time axes. The cause of this is mainly the “learning under the baseline” that creates different starting situations for our experiments.

In the model, we can now switch off different dynamics step-by-step. First, the additional “learning-by-doing” induced by a carbon tax is completely switched off (learning is equal to baseline), resulting in Figure 8.8 (upper right graph). Instead of reaching a maximum reduction near 60%, the maximum reduction is now 40-50% (lower right corner). Thus, induced learning between 2000 and 2030 to a 300 US$/tC tax creates an additional 10% response under the B2 assumptions relative to the response that would be obtained if no induced learning was included in the model. Interestingly, the difference between the first and second graph becomes less for the cases where there is a shorter period between the year of introduction and the recording time. This result can be understood, as this also decreases the period in which induced learning can take place.

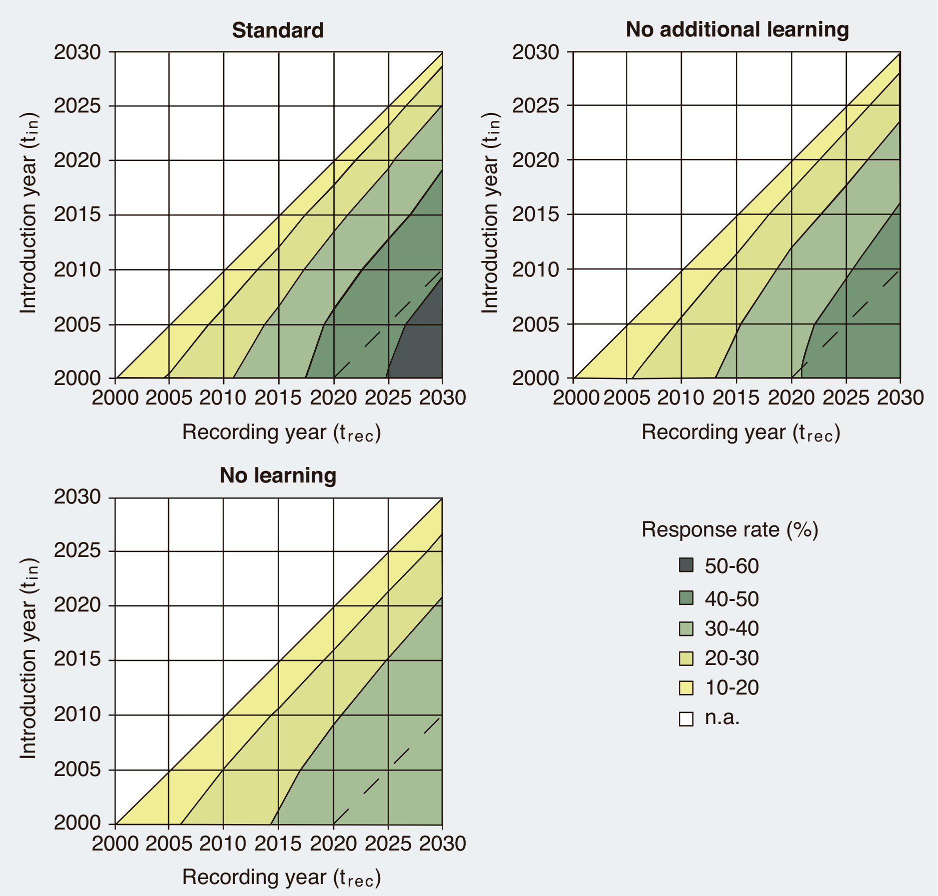

Figure 8.8 Global carbon response rate (in % reduction compared to baseline) to a US$300/tC tax as a function of introduction and recording year. The introduction year represents the year the tax is introduced, the recording year the year that the response to the tax is recorded. The dashed line indicates, as an example, all points in which the response is recorded 20 years after the introduction.

In the last experiment, we also switched off all learning that had already occurred in the baseline – leaving all technology frozen at its 2000 level[viii] (Figure 8.8; lower left). This means that inertia completely determine our results. Again, taking out the process of technological development reduced the response of the system to the carbon tax. The maximum response is now around 35% for the 2000 introduction, and 2030 recording years(lower right corner), thus, again, a loss of about 10% in terms of carbon emission reduction. Secondly it was observed that the graph had become more symmetrical. This is consistent with our explanation that the asymmetric response shown in the first two graphs of Figure 8.8 is at least partly related to learning under the

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[viii] Obviously, this also changes the baseline itself in terms of emissions. However, as we are interested in relative responses, this does not create major obstacles for comparing the different cases.

baseline. The remaining asymmetry is caused largely by depletion of fossil fuels in time (weakening the competitive position of fossil-fuel based technologies).

This set of experiments shows the importance of assumptions about technology development for the effectiveness of reducing carbon dioxide emissions – and for the abatement costs, if we take the level of the carbon tax as a proxy for total costs. In our experiments, we have more-or-less untangled the different roles of technology development in the baseline, induced technology development and inertia. Both induced technology development and technology development in the baseline contribute to 10% more reduction of carbon dioxide emissions in the case of a 300US$ tax introduced in 2000 and recorded in 2030. Inertia is very important as well, and on its own leads to a difference of between a 10% reduction of global emissions after five years and a 35% reduction after 30 years. It should be noted that these results reflect the full dynamics in the (simulated) world energy system, including depletion and trade.

8.5 Discussion and main conclusions

We have studied a set of different mitigation experiments, with a particular focus on the role of technologies in terms of mitigation responses to a carbon tax.

In interpreting the results of these experiments, we obviously need to take into account the model characteristics and assumptions. TIMER is an energy system model with a strong focus on relevant dynamic relationships among the various mitigation options but without macro-economic feedbacks. A second point of consideration refers to the baseline and the options that were used in our mitigation scenarios. The IMAGE B2 baseline, used as a baseline for our analysis, should be regarded as a medium- to low-emission scenario, so that most of the reductions studied here can be regarded as reductions with a medium level of ambition (e.g. a 40% reduction of carbon emissions required by 2100 to reach stabilization at 550 ppmv). On the other hand, the TIMER 1.0 version does not include all available mitigation options, which holds, in particular, for carbon sequestration, whether by means of capture and storage or sink enhancements.

Using an energy model in the context of an integrated assessment model allowed us to study some indirect changes of climate policies as well. First of all, the changes in the energy system in response to the carbon tax not only change carbon emissions but also other greenhouse gases and sulfur emissions. We have shown here that the environmental effectiveness – certainly in the short term – is limited as a result of a reduction in the aerosol cooling effect. Secondly, the integrated analysis used shows some of the trade-offs between reducing energy-related carbon dioxide emission by using biofuels and the impact of the analysis on land-use emissions. In our current results, biofuel use has a net mitigation effect, but some of the mitigation is offset by the additional demand for agricultural land, which increases land-use emissions.

The results lead to the following main conclusions.

- **Technological improvement is a crucial aspect of climate mitigation strategies.** This is shown in the case of the first two experiments, for instance, by cost reductions in solar/wind technology. This is most clearly observed in the results of the last set of experiments. Leaving out all forms of technology development reduces the response to a 300 US$/tC carbon tax in 2030 from a 60% reduction to only 30% (both compared to the baseline). Partly as a result of these technology developments, stabilization at 550 ppmv from the IMAGE B2 baseline appears feasible at relatively low costs through the introduction of a uniform carbon tax and a variety of measures induced by this tax. Interestingly, the costs and measures taken in going from B2 to 550 stabilization are more-or-less comparable to those found earlier in going to a 450 ppmv stabilization target from the B1 baseline (van Vuuren and de Vries, 2001). This shows how important baseline assumptions can be for the costs of reaching different stabilization levels; particularly the sustainable development orientation and the strong technology development assumed in the B1 baseline can allow for reaching lower stabilization levels at bearable costs when compared to other baseline scenarios.

- **In breaking down the results for the B2-550 stabilization scenario, an improved efficiency is shown to be the single most important factor in the first decades in terms of the mitigation response. However, from 2030 onwards, introduction of carbon-free supply options provides the bulk of the required reductions.** As a result, the changes in global energy intensity remain near the upper end of the historically observed range, whereas decarbonization rates reach levels above historical rates for the whole century. In terms of energy carriers, the sharpest reduction takes place for coal: 50% reduction in cumulative coal use. This implies that the greatest changes take place in regions with high shares of coal consumption or production. Alternatively, these regions might need to develop carbon storage capabilities (excluded in our experiments). In terms of fuel trade, carbon-tax induced changes in oil trade appear to be modest. Changes in trade of other energy carriers may be of the same order of magnitude and, depending on the region, work in the same direction as changes in oil trade – or completely offset them. The latter is, for instance, the case for the Former Soviet Union, where natural gas and biofuel exports offset the losses in oil exports.

- **Technology development needs to be studied in the context of other dynamic processes that are important to the world energy system.** In our simulated B2 world of the TIMER model, early-action scenarios result in accelerated technology development in the short and medium term. In the long term, however, there are a number of processes that may work in the opposite direction, such as the maximum share of renewable technologies that can be absorbed in the electric power system without additional costs, and the impacts on the depletion of both fossil fuels and renewables. These results depend on the assumptions made. In the current runs, scenarios with early carbon taxes lead to lower carbon dioxide concentrations in

2100. However, in 2100 they show similar emissions reduction as the scenarios with a slower introduction of the same carbon tax levels. It is important to study the role of these dynamic processes in more detail.

- ***Three technological processes that have a direct influence on the mitigation response to carbon taxes are the technology development in the baseline, induced technology development as a result of climate policy and inertia.*** **The relative importance of these different processes is directly related to the discussion on timing of mitigation action.** In our analyses, we have indicated how these processes all play a role. Learning that is part of the baseline will indeed make a 2030 response to a 2020 tax that is 5-10% higher than a 2010 response to a 2000 tax. However, the other two processes work in the opposite direction and are, at least, just as strong. Induced learning results in a 10% larger emission reduction in response to a 300 US$/tC tax in 2030; without learning, inertia will result in a 10% reduction of global emissions after five years and a 35% reduction after 30 years. Collectively,, the processes over this short time period of evaluation that support an early action response seem to dominate over the processes that favor a delayed response approach – at least, if no discount rate is applied. At what discount rate the balance shifts to a preference for a delayed response approach has not been analyzed here. In any case, the dynamics behind different technological processes have been found to be very important to understand the system response to carbon prices . Providing sufficient pressure to stimulate low technology development in the direction of carbon energy systems seems to be crucial. Sufficient resources for research and development, and climate policies, can help to facilitate the developments in this direction.