Climate policy and economic dynamics:

the role of substitution and technological change

PROEFSCHRIFT

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Contents

CHAPTER 1

Introduction

"...it is extremely likely [i.e. with at least 95% confidence] that humans have exerted a substantial warming influence on climate." – Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Forster et al., 2007, p. 131)

"The ultimate objective of this Convention (...) is to achieve (...) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." – Article 2 of United Nations Framework Convention on Climate Change (UNFCCC)

With the coming in force of the Kyoto Protocol in February 2005, an environmental-economic policy of unprecedented scale became active. The Protocol lays binding emission limits for greenhouse gases on a group of more than 30 countries, responsible for more than 40% of global carbon dioxide emissions in 1990. The Kyoto Protocol, which is a protocol to the UNFCCC, assigns to these countries greenhouse gas emission reduction targets.[1] For example, the EU-15 should reduce its emissions to 8% below its 1990 emissions, over the period 2008-2012. Effectively this puts a ceiling on that country's greenhouse gas emissions: although its economy is

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[1] The group of countries subject to the Kyoto Protocol excludes the United States, who signed the Kyoto Protocol but did not ratify it, and developing countries like China and India. In addition, some of the countries that ratified the Protocol have smaller economies than in 1990, most notably countries of the Former Soviet Union, and will in any case emit less greenhouse gases than allowed under the Protocol.

allowed to develop and grow the way it wants, emissions are not allowed to exceed their target.[2]

The main purpose of this thesis is to study the dynamic effects that such a ceiling on emissions has on the economy. Questions that will be answered include: What is the effect of the emission ceiling on the optimal use of fossil fuels like coal, oil and gas? To what extent will emissions of greenhouse gases be shifted from countries subject to the Kyoto Protocol to countries that did not ratify this treaty? What is the role of carbon-saving technological change in this? Is announcement of climate policy, giving the economy time to prepare, always a good thing to do? Is the production structure of dynamic quantitative models for climate policy adequately modeled?

To place this thesis in the literature on the economics of climate change, we first present a brief introduction into the literature on the economics of climate change. In section 1.1.1 we present a brief discussion of this. Then we move on to the literature on the design and consequences of climate policy in section 1.1.2. The current thesis can be placed in this part of the literature on the economics of climate change. Section 1.1.3 gives a brief overview of the literature on the formation of international environmental agreements. We present the specific research questions and some conclusions of this thesis in section 1.2. Section 1.2.3 summarizes the main findings of this thesis, and presents some good news and some warnings for proponents of climate policy and policy makers.

1.1 The economics of climate change: a short introduction

The effects of an increased concentration of greenhouse gases in the atmosphere, are (1) long term, (2) uncertain, (3) potentially catastrophic and (4) unequally distributed over our planet and over time (Goulder and Pizer, 2008). In addition, climate change control is a global public good: all countries benefit from a single country's reduction in greenhouse gas emissions (Carraro, 2002), and hence each country has an incentive to free-ride on other countries' emission reductions. These characteristics make climate change a unique economic problem that has to

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[2] Under the Protocol, countries are allowed to achieve a part of their targets through emission reductions abroad. Through the Clean Development Mechanism, for example, countries can finance projects in developing countries to reduce greenhouse gas emissions over there, and add these emission reductions to their own record. However, there is a maximum of emission reductions that each country is allowed to achieve abroad, and once these cheap emission reduction possibilities are exploited, each country (or Party in terms of the Protocol, as the EU-15 operates as one unit) has to reduce emissions domestically.

be studied from different angles, and hence the field of climate change economics has developed in several directions. A first question that arises with climate policy is what is the optimal amount of climate change mitigation, and what is its time path? We briefly discuss this topic in section 1.1.1. Given the path and amount of mitigation, optimal or not, the next question is how the mitigation target can be achieved at lowest costs, and what the effects of the policy will be on all kinds of economic variables including GDP and employment? This literature will be discussed in section 1.1.2. Section 1.1.3 briefly discusses the literature on how a coalition of countries can be formed to jointly introduce international climate policy.

1.1.1 Optimal climate policy

Integrated Assessment Models: from DICE-99 to DICE-2007

To answer the question ’what to do with a changing climate?’ economists would preferably do a cost-benefit analysis (CBA). First determine the costs of several climate change scenarios and the costs and benefits of the associated policies (both in terms of avoided costs from climate change, and the direct costs that the policy puts on economic agents), and then determine the policy that yields the largest net benefit.

The literature on optimal climate policy relies heavily on integrated assessment models (IAMs). These are models that link a simplified climate module with a global model of optimal GDP growth, that seek to find the optimal policy which trades off expected costs and benefits of climate change control (Kelly and Kolstad, 1999). Two well-known models that were very influential in the 1990s are the DICE (first published in Nordhaus, 1992) and RICE (Nordhaus and Yang, 1996) models. The latter paper compares the optimal policy for the case where each of 10 world regions maximizes its own sum of discounted future streams of utility with the optimal policy for the case where *global* net present value of utility is maximized, using the RICE-94 model. Since the costs of emission control are high while the benefits are in the far future, the economically efficient strategy (according to Nordhaus and Yang, 1996) is for only a small reduction in CO_2 emissions (compared to the case in which climate does not affect welfare). The optimal reduction rates in case of global cooperation are highest for developing countries (rising from 17% 2000 to 22% in 2070 for China) and lowest for industrialized countries (rising from 7% to 12% for Japan). Nordhaus and Yang (1996, p. 752) use this analysis to argue against the Kyoto Protocol: “The only potential rationale for the Framework Convention is that it puts a very high weight on equity (by relieving poor countries of obligations to reduce emissions) and rules out the possibility of side payments (say through allocation of emission permits).” Nordhaus and Yang conclude that “Countries may

(...) be triply persuaded not to undertake costly efforts today – firstly because the benefits are so conjectural, secondly because they occur so far in the future, and third because no individual country can have a significant impact upon the pace of global warming.” (p. 762) In an overview of integrated assessment models, Kelly and Kolstad (1999) conclude: “Probably the most striking result is that our current understanding of climate change costs and damages does not justify more than modest emissions control given a discount rate calibrated from interest rates and slow economic growth. The optimal amount of emissions control is well below currently proposed policies [i.e. the Kyoto Protocol], yet more than the (...) policy of doing nothing.” (p. 192)

Over time, however, Nordhaus has changed the parameters underlying his models, to bring the model closer to intergenerational neutrality. This was not feasible in the past, as the increased nonlinearity of the model under the new parameter construct was too difficult to solve numerically (Nordhaus, 2007a). The insights the models provide have changed accordingly. The DICE-2007 model, for example, finds optimal global emission reduction rates of 14% in 2015, 25% in 2050 and 43% in 2100, and calls the policies currently in place “meager” (Nordhaus, 2007b, p. 698). Compared to the DICE-99 model, this increase in the optimal amount of emission reductions stems for over two-thirds from a change in the damage function (reduced estimated benefits of warming at low rates of warming for some regions), for about a quarter from a reduction in the discount rate from 3% to 1.5% (to reduce the market interest rate, joint with a doubling of the consumption elasticity from 1 to 2, using the Ramsey rule; see below), and for about 5% from a slight increase in the temperature sensitivity coefficient; projection errors and composition effects regarding world output have led to a slight (some 2%) counter-effect (own calculations, based upon Nordhaus, 2007a).

It should be noted that the models just described did not include endogenous technological change. Popp (2004) extends the DICE-99 model with endogenous technological change, but finds that it hardly affects the path of optimal climate policy. However, it substantially increases the policy’s welfare gains through cost reductions (compared to the case of optimal climate policy with exogenous research and development).

Ethical choices and the consumption discount rate

The second quote from Nordhaus and Yang (1996) above reflects most of the characteristics of the climate change problem mentioned in the introduction of this section. Indeed, although the textbook solution of equating marginal benefits of harmful emissions with the marginal costs of emission reductions is feasible for several environmental problems, the four characteristics of the effects of increased greenhouse gas concentrations, described above, make this solution very hard for the case of greenhouse gases. That is, it is hard to come with an *optimal* climate policy, and it is probably impossible to come with a proposal of optimal policy without taking some ethical decisions when deriving this optimal policy.[3] Should emissions be reduced in developing countries, as there emission reductions can be achieved at lowest costs? Or should OECD countries, responsible for some 65% of the increase in CO_2 concentrations since 1750 (Raupach et al., 2007), take their responsibilities and start reducing first? How should welfare of future generations be taken into account, that is what discount rate should be chosen when determining optimal policy?

As global warming is a long-term issue (CO_2 that is emitted now may stay in the atmosphere for over 200 years), the results from optimal growth models are very sensitive to the choice of discount rate in integrated assessment models. This point makes clear that climate change is an intertemporal and intergenerational problem, and is nicely illustrated by the recent discussion around the 'Stern Review on the economics of climate change' (Stern, 2006). The Review, a political document initiated by the British government, argued in favor of strong current climate mitigation policies, since, according to the Review, the benefits of early action outweigh the costs. As several economists were quick to point out, this conclusion largely comes from the choice for a near-zero discount rate (Nordhaus, 2007b, Weitzman, 2007).

Some of the results of the Review come from an integrated assessment model called PAGE, and as in any optimal growth IAM the discount rate crucially appears in the Ramsey equation: $r = \rho + \eta g$. Here r is the consumption discount rate (also called market interest rate), ρ is the rate of pure time preference, η is the elasticity of marginal utility (or, equivalently, the coefficient of relative risk aversion), and g is the per-capita growth rate of consumption.[4] Using the Review's values of $\rho = 0.1\%$, $\eta = 1$, and $g = 1.3\%$, we get a consumption discount rate of 1.4%. That is, a loss 100 years from now of €100, for example coming from climate change, is presently valued as a loss of €24.90. Nordhaus (2007b) and Weitzman (2007) argue that the Review's choices for η and ρ are at the extreme lower bound of what is considered 'reasonable' in economics. In addition, both authors argue that the implicit sav-

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[3] Indeed, van den Bergh (2004) argues that "an overall quantitative CBA evaluation and comparison of policy options that aim to reach distinct reduction percentages, as well as a choice of optimal climate policy based on models of optimal growth, are overly ambitious." (p. 385)

[4] Instead of 'consumption discount rate', authors frequently label r the interest rate or return on capital (see e.g. Weitzman, 2007, Nordhaus, 2007b). However, r equals the return on capital only if there are no market failures with respect to consumption (with growth rate g in the equation), and only with perfect foresight on all capital markets (see e.g. Heal, forthcoming). Heal argues that since climate change is a large external effect, and given the current crisis in capital markets, the Ramsey equation cannot be used in the climate change debate.

ings rate resulting resulting from the choice of parameters in the Stern Review is too high. Nordhaus chooses $\eta = 2$ and $\rho = 1.5$ in his DICE-2007 model, combined with a growth rate of (on average) 2.25%, and hence uses an interest rate of 6%. With this rate, a loss 100 years from now of €100 is presently valued as a loss of less than 30 cents: a difference of two orders of magnitude.[5] Nordhaus (2007b) finds a much lower optimal carbon tax than the Stern Review (initially, $35 versus $350, and about $180 versus close to $1000 for the year 2100), albeit higher than the expected carbon price stemming from the Kyoto Protocol. Clearly, the Review's choice of a very small discount rate, compounded by a low value for the elasticity of marginal utility, put the odds strongly in favour of immediate emission reductions for any given expected future damages.

Weitzman (2007) goes even further than Nordhaus in his critique on the Stern Review. Given the uncertainty surrounding climate change itself (see e.g. Tol, 2005), there is uncertainty about future rates of return, leading to low riskfree rates of return and higher risky rates. Following the framework of the Ramsey equation, the uncertainty comes from uncertainty about future economic developments, that is uncertainty about g. The fundamental question is whether in principle the *risk-free* rate or the *risky* economy-wide rate of return should be used for discounting the costs and benefits of climate change. This depends on the correlation between the return to the climate-related project and the return to the economy as whole. Weitzman (2007, p. 713) argues that this correlation coefficient might be significantly smaller than one: "Instances of changes in "outdoor" activities under global warming include what happens to tropical agriculture, losing significant parts of Bangladesh (or Florida) to rising sea levels, the "consumption" of an altered natural world that is a direct argument in the utility function, and so forth. These kinds of changes, which include the existence value of natural environments, are presumably not highly correlated with technological progress in computing power, furniture making, or better pharmaceuticals a century from now." The higher the correlation, the closer the rate of return should be to the risky economy-wide rate of return. Since the observed risk-free rate is about 1% and the risky rate is about 7%, the subjective choice to be made here, has a huge influence on the cost-benefit analysis. Hence the problems of a cost-benefit analysis stemming from uncertainty about future costs and benefits of climate change are compounded by uncertainty about the choice of interest rate to use in the discount factor.

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[5] Combining Stern's values for η and g with Nordhaus' $\rho = 1.5\%$ and combining Nordhaus' parameters with Stern's rate of pure time preference give a present discounted value of €6.32 and €1.80 respectively, both still much smaller than the Review's €24.90. Heal (forthcoming) argues that if one does use the Ramsey equation (contrary to his suggestion; see footnote 4), the reasoning should be from ρ to η, r and g, as there is certainty about the former parameter (according to Heal, it should be zero, which is even lower than the Review's 0.1%), whereas all other parameters are uncertain (and g is a variable).

More problems with IAMs

In addition, Heal (forthcoming) shows that moving from a one consumption good world to a multi-good world, including environmental services, the cross-elasticity of marginal utility between two goods might be negative (if the goods are complements), and hence the consumption discount rate of a particular good might be smaller or larger than the return on capital, and might even be negative. Another interesting point made in Heal (forthcoming), concerns the role of η. As η rises, the marginal utility of consumption falls more rapidly. Assuming that future consumption will grow, larger values of η imply that we place less value on stopping climate change. However, η also plays a role in the intratemporal dimension: a higher value implies a stronger preference for equality. Given that a lot of the damage from climate change falls on poor countries, this should lead to stronger action. However, all IAM's, including DICE, only capture the first dimension, leading to the result that a greater preference for equality leads to less concern about climate change. Therefore, multi-good (including environmental goods) multi-consumer (country) models are needed.

The biggest problem with cost-benefit analysis for climate change might come from low-probability high-impact events, or "rare disasters" in brief. Weitzman (2007) deduces from table SPM-3 of Intergovernmental Panel on Climate Change (2007) that the probability of a temperature increase of 6°C in the coming one hundred years is "very roughly about 3%". Both the size of the temperature increase and the relatively short time-scale (from a climate and ecology perspective) make this temperature increase a disaster. Moreover, the fact that disasters are rare makes their probability itself hard to estimate, while at the same time it is unforeseeable what will be the economic damage (the resulting negative value of parameter g) associated with the disaster. In short, there is uncertainty about the uncertainties which leads to a probability distribution of g with a thick left tail. "Mitigating the future consequences of greenhouse warming does not just shift the center of the distribution of g to the right but, perhaps far more importantly in this context, it thins the left tail of the distribution as well." (Weitzman, 2007, p. 718) Weitzman therefore suggests to have a time out for the next decade by investigating seriously the nature of the disasters in the thick tails and what might be done realistically about them if they arise, instead of immediately and dramatically reducing greenhouse gas emissions as suggested by the Stern Review. Van den Bergh (2004) uses similar arguments to argue for a qualitative rather than a quantitative cost-benefit analysis in the economic analysis of climate policy. According to Leach (2007), it may take thousands of years to learn the true parameter values of the climate model, which goes against the suggestion of Weitzman, and is yet another reason not to rely too heavily on quantitative optimal climate policy models.

Heal (forthcoming) compares the results and assumptions of several papers, including Stern (2006) and Weitzman (2007), and concludes that "...there are several ways of concluding that we need to take action. We can follow the route of the Stern review and use a low discount rate and set $\eta = 1$, or we can allow for climate impacts on ecosystem services, or we can be explicitly concerned about the risk of an outcome in the tail of the distribution of possible outcomes. Any of these seems sufficient to justify immediate action. And several of them seem plausible." (Heal, forthcoming, p. 21)

1.1.2 Design and consequences of climate policy

Given some climate policy target (the answer to the question: How much to abate?), several questions can be asked regarding the abatement policy:

- What to abate?
- How to abate?
- Where to abate?
- When to abate?

When an agent is free in choosing the answers to these questions, she has maximum flexibility in meeting the objective. Hence, the objective can be met against the lowest cost and policy is cost-efficient. The Kyoto protocol gives all participants an emissions target, but leaves the questions above mostly unanswered. Countries themselves can choose *what* to abate, that is which emissions (CO_2, methane, nitrous oxide) to reduce. So if a country can reduce emissions of methane at a lower cost than emissions of carbon dioxide it will first reduce emissions of methane, up to the point where the costs of reducing methane are equal to the costs of reducing carbon dioxide emissions.

According to the Kyoto Protocol, countries can choose themselves *how* to reduce emissions, that is which instruments to use: taxes, standards, tradable permits, and carbon sequestration. Furthermore they can decide *where* to reduce these emissions. Not only can they choose where to do it within their own borders but, countries can also fulfill part of their requirement by paying for reduction of emissions in other regions subject to the Protocol (Joint Implementation) or in developing countries (Clean Development Mechanism). Although one might argue that this will lead to a decrease in emissions by countries outside the Protocol, there are other forces that might lead to emission increases in these countries. We will study this problem of 'carbon leakage' in chapter 4.

There is less flexibility in *when* to abate. Countries may see opportunities to abate against lower costs in the future, for example because of expected technological developments. However, within the Kyoto Protocol the targets of the regions are formulated for the ’commitment period’ 2008-2012, so they can only postpone emissions within these five years. Furthermore, since the Protocol was agreed upon in 1997, and entered into force in 2005, this still left countries free in their emissions before 2008. As will be argued in chapter 3 of this thesis, the fact that agents new some years in advance that they would be constrained in their emissions at some given point in time (the commitment period 2008-2012), might have led to an *increase* in emissions in the period before 2008.

We now briefly discuss the ’what’ and ’how’ questions, and then give a short overview of the literature on the economic effects of climate policy.

What to abate?

Although a lot of attention in the popular and scientific press goes to carbon dioxide emissions, other greenhouse gases, notably methane and nitrous oxide, are important contributors to global warming as well. The Kyoto Protocol covers these gases as well, and, as noted above, if countries find it cheaper to reduce emissions of these gases, they are free to do so. Emission reductions from these gases are then converted in to CO_2 equivalents, and are counted for their emission reduction target.

In addition, although carbon dioxide is largely emitted by industrial processes, it can be sequestered through agricultural activities. Indeed, carbon sequestration through forestry (see e.g. Lee et al., 2005) or through soil management in agriculture (see e.g. Antle et al., 2001) can help to provide low- or even negative-cost near-term climate policy strategies, buying time for technological developments (Lal, 2004).

How to abate?

Regarding the question on how to abate, that is what instrument to use, it can be shown that for many environmental problems both a tax on pollution and a system of a cap on emissions with tradable permits can achieve an environmental target at lowest cost. That is, both instruments are cost-efficient. In addition, both instruments are dynamically efficient, as they give firms incentive to invest in research and development, to further reduce emissions. Fischer et al. (2003) do not find a general preference for auctioned permits over emissions taxes and emissions taxes over free permits, when technological change is endogenous. Under different circumstances either auctioned permits or taxes can induce larger amounts of innovation but any of the three policies may induce a significantly greater welfare gain than the other two. The relative ranking of policy instruments depends on the scope for imitating new technologies, the costs of innovation, the relative level and slope of the marginal environmental benefit function, and the number of polluting firms.

Weitzman (1974) showed that taxes and permits are not equivalent when marginal benefits and costs of abatement are uncertain. In that case, the relative slopes of the two curves determine which policy will be better. Permits are preferred when the marginal benefits are steep and marginal costs are flat. In that case, it is important to get the quantity of emissions down to a threshold, which is exactly what a permit policy does. In the opposite case, however, a (carbon) tax would be a better policy. In general, the marginal cost curve for reducing greenhouse gas emissions is considered to be steep, while the nature of climate change indicate that the marginal benefit curve for reducing emissions will be very flat (McKibbin and Wilcoxen, 2002). Given that carbon dioxide is a stock pollutant, an additional unit emitted now has about the same impact on global warming as an additional unit emitted in one year time, and a carbon tax is preferred. In practice, however, (Pigouvian) taxes are not as often used as one might expect. One reason for this might be the hostility of firms to the large sums of money that have to be payed to the government: even when a firm reduces its emissions of a pollutant by 30%, it will have to pay taxes over the remaining 70%. In a permit trading system with grandfathering (common praxis for Phase I of the European Union Emissions Trading System and Phases I and II of the US Acid Rain Program) on the other hand, firms only need to buy the permits that they need to fill the gap (if any) between actual emissions and received permits.

In order to reduce emissions, only the last unit of emissions needs to be priced. This, however, is hard to do in practice. Vollebergh et al. (1997) therefore argue in favour of either a carbon tax with credits, or a system of permits with partial grandfathering, which reduce the overall transfer from firms to the government, but still leave incentives to reduce emissions at the margin untouched.

Another advantage of taxes over a system of (grandfathered) permits is that the receipts from carbon taxes can be used to lower other taxes through a revenue-neutral governmental policy. Given some target of emission reductions, distorting taxes on, for example, labour can be reduced in such a way that the government's foregone labour-tax receipts are exactly offset by the receipts from a carbon tax (or a tax on greenhouse gases in general, converted into carbon-equivalents). The weak form of the 'double dividend hypothesis' in environmental economics states that the (non-environmental) efficiency costs of such a revenue-neutral environmental tax reform are lower if the additional revenues from the environmental taxes are recycled in the form of lower distortionary taxes compared to the case that these revenues are recycled in a lump-sum fashion (Bovenberg, 1999). Although this hypothesis is widely accepted among economists (Schöb, 2005), the *strong* double dividend hypothesis, which asserts that an environmental tax reform enhances not only environmental quality but also non-environmental welfare, is strongly debated (see Bovenberg, 1999).

Although there are several arguments for a (global) carbon tax, instead of a system of tradable permits, it is quite likely that the future will see a cap-and-trade system for greenhouse gases, as the institutions for such a system are already available. First, the Kyoto Protocol effectively puts caps on participating countries, and it is likely that negotiations for a post-Kyoto climate agreement will build upon the experience gained during the 2008-2012 period that is covered by the Protocol. Second, the European Union has introduced the EU Emission Trading System: a system where tradable permits are allocated over firms in the European Union, which then can trade these permits on permit markets. Although currently only the EU is involved, other regions, ranging from Europe's Norway to several US states, have indicated to be interested in joining the scheme in the future.

Although taxes and permits are considered to be the most efficient instruments to achieve a certain environmental target, they can be supported by other policies, insofar as they correct for other externalities. The most important additional policy is probably technology policy. As climate policy is a long-term problem, cleaner technologies are generally expected to lead to most of future emission reductions. For cleaner technologies to appear, however, it is important to put a price on greenhouse gas emissions, for example through a tax or through a cap-and-trade system. With these instruments, firms have an incentive to reduce emissions as long as the marginal benefits of doing so (foregone taxes, or the receipts of selling emission permits) exceed the marginal costs. However, technological change has an important market failure with it, stemming from the public good characteristic of knowledge. Once a new technology is introduced, it is available for use by other agents, without having to incur the costs of research and development. As a consequence, the firm that has done the initial investment can not cover the cost of this investment by charging a price over its marginal cost, and no firm can profitably invest in new knowledge. Hence, a system of (and enforcement of) intellectual property rights is needed, to fix the market failure of knowledge spillovers. With a system of patents, a firm that has developed a new technology can get a temporary monopoly on its technology (which allows the firm to cover the costs of research and development with monopoly profits), but in return it must publish its findings, such that other firms can use the results to develop further new technologies. Therefore, the social return to knowledge is widely believed to be much higher than the private return (for example, Jones and Williams (1998) find that the social return is two to four times higher than the private return), which suggests that there is room for technology policy, such as subsidies to research and development.

Economic effects of climate policy

There is a substantial literature on the assessment of the (macro)economic effects of climate policy, especially with respect to the Kyoto Protocol. Regarding quantitative modeling, during most of the 1990s this literature was divided along two types of models used. On the one hand there was a literature using bottom-up models (see e.g. Messner, 1997, Barretto and Kypreos, 2004). These models have a detailed representation of technological possibilities in energy sectors, but generally lack an adequate representation of other sectors in the economy, in particular final demand for energy. Second there were top-down models (see Carraro, 2002, for an overview). These are mostly computable general equilibrium (CGE) models, and they generally have a multi-sector (and often multi-country) representation of the economy and are able to represent changes in demand for several goods, including energy, that come from climate policy.[6] The drawback of these models is that the technological opportunities of the energy sector are not modeled in detail, leading to higher cost estimates than those from the bottom-up literature. The flip side of the coin is that the latter literature may be too optimistic: the availability of a cleaner technology does not imply that it will be adopted by firms. This depends on several underlying economic factors that are generally lacking in these models. The recent literature tries to combine the top-down and bottom-up characteristics in hybrid models (see e.g. Böhringer and Rutherford, 2008, Bosetti et al., 2006, Sue Wing, 2008).

The literature on the effects of climate policy on the macro-economy is very broad, and uses both analytical and quantitative models.[7] In the policy debate, the policy's effects on output and employment have received most attention. In the scientific debate this comes back in the literature on the double dividend hypothesis mentioned above, which studies the effects of environmental policies on output and employment (see Bovenberg, 1999, Schöb, 2005, for references). We will now only briefly touch upon the topics that are related to the chapters of this thesis; more extensive literature overviews can be found in the respective chapters.

The literature on carbon leakage studies the effects of climate policy on trade flows and emissions by regions that are not subject to climate policy (see for example

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[6] Within the group of top-down models there are a few macroeconometric models as well, see for example Jorgenson and Wilcoxen (1996). Integrated Assessment Models can fall in each of the two categories, depending on the model's details. Over time, the two groups of models have moved closer, as bottom-up models gained in economic detail, while top-down models gained in the modeling of energy supply and energy technologies.

[7] In this thesis, we use analytical models to study some of climate policy's effects on the behaviour of economic agents.

Copeland and Taylor, 2005, Hoel, 1996, Ishikawa and Kiyuno, 2006). Carbon leakage will also be the subject of scrutiny in chapter 4.

Second, any policy that affects relative prices will induce substitution effects, between goods and between inputs, as agents will want to substitute away from inputs that have a higher relative price. Substitution between (energy) inputs, as induced by climate policy, is explicitly studied in Chakravorty et al. (1997), Chakravorty et al. (2006), Chakravorty et al. (2008). In these papers, the optimal extraction paths of fossil fuels are studied in the presence of climate policy. Chapter 2 of this thesis is closely related to this literature.

Recently the relation between climate policy and technological change has received a lot of attention. This literature has been reviewed in Löschel (2002) and Jaffe et al. (2002), but even though these reviews are quite recent, they are already outdated, as since their publication a wave of publications on this topic can be found. Examples of these are the special issues of *Resource and Energy Economics* in 2003, *Ecological Economics* in 2005, *The Energy Journal* in 2006 and *Energy Economics* in November 2008. Part II of this thesis also studies the relations between climate policy and technological change.

Finally, it should be noted that CGE models are also used to study the (expected) economic effects of a changing climate. As CGE models are generally based on a competitive economy, these models generally only take market damages due to climate change – changes in productivity (especially of agriculture) or coastal zones (see for example the special issue of *Ecological Economics* of August 2007), increases in probabilities of diseases, etc. – into account. However, large benefits of climate policy come from the prevention of non-market damages. For example, a less hospitable climate affects utility but not necessarily productivity; ecosystem services and biodiversity can have option and existence values, that are not reflected in market prices.

1.1.3 Coalition formation

The previous sections have discussed climate policy as performed by a country, a group of countries, or the world as a whole. That is, we assumed that there exists a country or group of countries (coalition) that implements policies aimed at reducing greenhouse gas emissions. In the remaining chapters of this thesis this is assumed as well. The question is then how such a coalition of countries, that voluntarily reduces its emissions of greenhouse gases, can be formed.

The main characteristic of international environmental agreements (IEAs), like the Kyoto Protocol, is that there is no international agency that can establish binding agreements. Hence, IEAs have to be profitable for all potential participants (Finus, 2003). This first point is clear from observing the discussions around the Kyoto

Protocol over the last 10 years. The United States and Australia did not ratify the Kyoto Protocol as they expected its costs to be larger than its benefits. In addition, developing countries indicated to put more weight on economic growth than on cutting greenhouse gas emissions.

In this section we briefly discuss the problems surrounding the formation of an international environmental agreement (for recent reviews, see Finus, 2003, Folmer and von Mouche, 2000). As welfare levels of countries in the context of climate change and climate policy are interdependent, the topic of coalition formation is best studied using game theory. We focus on what Finus (2003) calls 'membership models': models where countries can free-ride by either not being a member of an IEA, or being a member of an IEA that contributes less to the improvement of environmental quality than members of other agreements.[8] These models are concerned with the coalition formation process and stability of membership. Furthermore, we focus on the results from non-cooperative game theory, which assumes that binding agreements are not possible.[9] The subject of this literature is on internal and external stability. A coalition of countries that signs an international environmental agreement is internally stable if there is no incentive for a participant to leave the coalition, and it is externally stable if there is no incentive for a non-participant to join the coalition. If a country leaves the coalition, its members punish by increasing their emissions.

When countries are symmetric, and in the absence of transfers, the number of participants usually falls short of the grand coalition (which covers all countries), and is hence socially sub-optimal (Finus, 2003, p. 109). The larger the coalition, the larger are the benefits from free riding. Furthermore, given the size of a coalition, the number of participants will be lower when the pay-off of an emission increase is higher. Indeed, whenever cooperation is most needed from a global point of view, international environmental agreements achieve only little (Barrett, 1994). When countries are asymmetric, cooperation is even more difficult, and the coalition is even smaller.

Linking a public-good agreement to a club-good agreement may increase participation of the environmental public-good agreement. The former type of agreement suffers from free-riding, while the latter type enjoys a higher participation since the gains from cooperation are exclusive to signatories (see for example Barrett, 1997). Indeed, issue linkage could be observed for the Kyoto Protocol as well. Kyoto only came into force after passing a threshold of participating countries'

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[8] A second branch of the literature on IEAs looks at compliance: whether members of an IEA will comply with its terms. The interested reader is referred to Finus (2003) and Barrett (2005).

[9] Cooperative game theory focusses on countries' decisions when facing the socially optimal emissions vector. This is mainly a normative concept and cannot be used to explain suboptimal treaties like the Kyoto Protocol (Finus, 2003, p. 104).

emissions, which was passed after Russia joined. However, one reason why Russia joined was that the European Union promised to support Russia's application for joining the WTO when Russia ratified Kyoto.

Another extension of the literature on coalition formation comes from reputation effects. If a country decides not to join an agreement, it might be bad for future negotiations on other topics. This reputation effect might have played a role at the United Nations Climate Change Conference in Indonesia, in 2007. At this conference, parties tried to agree on a 'roadmap' for a future (post-Kyoto) international agreement on climate policy, and the US were blocking an agreement for a long time. Only at the very last instant, when it was clear that most other countries condemned the attitude of the US, it agreed on the 'Bali roadmap'.

1.2 Research questions and overview of thesis

"...policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." – Article 3.3 of United Nations Framework Convention on Climate Change

The main purpose of this thesis is to study how climate policy affects the behaviour of economic agents (firms, consumers, resource owners) over time, and this thesis can therefore be placed in the literature discussed in section 1.1.2 above. The type of policy that is considered throughout this thesis is a ceiling on greenhouse gas emissions. The Kyoto Protocol effectively puts a ceiling on emissions for the group of countries that ratified it, and throughout this thesis we take a ceiling on the flow of carbon dioxide emissions as given. Hence, throughout this thesis we take the Kyoto Protocol as our starting point, and study optimal responses to a given climate policy (as opposed to studying optimal climate policy).

There are many reasons to dismiss the Protocol as 'optimal' climate policy: proposed emission reductions are only marginal from a global perspective, both the world's largest emitter (the US) and large and rapidly growing emitters like China are not subject to emission constraints, the Protocol's 5-year window causes a lack of certainty for firms to make long-term investments, etc. However, while many of the Protocol's flaws are a result of its underlying political processes, there are at the same time (political) forces that might fix these flaws. With the passing of time, there is more scientific knowledge about global warming and greenhouse gas concentrations, reducing uncertainties and increasing pressures to curb global emissions. Political forces in the US are in the direction of curbing greenhouse gas emissions, inside or outside a post-Kyoto treaty, while local pollution in China triggers the awareness of authorities to monitor the use of fossil fuels. There are strong international calls for a post-Kyoto treaty, while at the 2007 G8 summit in

Heiligendamm, Germany, climate policy stretching to 2050 was mentioned, which gives firms at least a hint that it might be beneficial to take up long-term investments in clean technologies. It is therefore likely that future multilateral climate policy will be based on the foundations of the Kyoto Protocol. We will hence take a ceiling on emissions as exogenous in the first three chapters of this thesis, and study several of its possible effects.

In this thesis, we will mainly focus on emissions of carbon dioxide that come from the use of fossil fuels. Although the Protocol covers 6 different greenhouse gases, most attention (both in science, in policy and in popular press) goes to carbon dioxide (CO_2), as this gas has led to a radiative forcing of 1.66 W/m^2 compared to a total radiative forcing of 2.63 W/m^2 (Forster et al., 2007, p. 131).[10] About three-quarters of the radiative forcing coming from carbon dioxide is caused by past emissions of fossil fuels and cement production (with roughly 3% coming from cement, see Denman et al., 2007, p. 517), with the remainder caused by land use changes (Forster et al., 2007, p. 131).[11]

The rest of this section discusses the research questions of this thesis in more detail.

1.2.1 Part I of the thesis: Climate policy and optimal extraction of fossil fuels

The economic effects of climate policy are often studied using either static models, or using models in which energy from fossil fuels is provided using some fixed factor. In reality, however, fossil fuels are nonrenewable resources: as it takes nature millions of years to create fossil fuels (coal, oil, natural gas) from the remains of plants and animals, the stocks of these resources are *de facto* given for humanity. As a consequence, when some amount of a resource is currently extracted, is no longer available for future generations, and the path of extraction of fossil fuels should be determined taking into account the needs of coming years and future generations. Hotelling (1931) has shown in a partial equilibrium setting that under perfect competition, the price of a nonrenewable should grow at the rate of interest, to make the resource owner indifferent between selling the resource today or at some later date. In this part of the thesis, we take this Hotelling model as the starting point, and study how climate policy affects the optimal extraction of two resources that differ in their carbon content (chapter 2), and how it affects the optimal extraction of a resource and the path of carbon dioxide emissions when

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[10] Radiative forcing is a concept used for quantitative comparisons of the strength of different human and natural agents in causing climate change.

[11] For an overview on modeling linkages between land use and climate policy, see Van der Werf and Peterson (2007).

climate policy is announced in advance (chapter 3).

Chapter 2: Climate policy and the optimal extraction of high- and low-carbon fossil fuels

Climate policy affects the relative prices of fossil fuels, e.g. through a carbon tax or through tradable permits. Since coal has a higher carbon content (per unit of energy) than oil, which in turn has a higher carbon content than natural gas, the standard static model of a Pigouvian tax suggests it will be optimal for firms to substitute towards the cleaner inputs oil and (especially) gas. In chapter 2, we take take the question of optimal fuel use under a carbon tax to a dynamic context. We model fossil fuels as nonrenewable resources that are imperfect substitutes at an aggregate level, and study the following questions:

1. (a) How does a ceiling on carbon dioxide emissions affect the optimal extraction paths of fossil fuels, and how does it induce firms to substitute between different fuels?
    (b) How are these results affected when the climate policy is announced in advance?

We show that the results of the static model can change dramatically when the more appropriate dynamic model is taken into account. Relative extraction of the fossil fuels not only depends on the respective carbon contents (and hence tax per unit of energy), but also on their relative productivity and physical scarcity. The best way to cope with an emission constraint is to intertemporally reallocate the extraction of the resource stocks such that production per unit of carbon dioxide emissions is relatively high during the period in which the emission constraint is binding, and low when the constraint no longer (or – in the case of an anticipated constraint – not yet) binds. Hence the constrained economy uses the resource with the lowest amount of emissions per unit of output relatively more intensively, as compared to an unconstrained economy. This resource is not necessarily the resource with the lowest amount of carbon per unit of energy: because of diminishing returns to each of the energy inputs, the scarcer a resource relatively is, the higher its marginal productivity per unit of emissions.

Our empirical results suggest that it is cost-effective to substitute away from dirty coal to cleaner oil or gas. However, when it comes to choose between relatively clean natural gas and the dirtier input oil, the paradoxical "dirty-first" result might apply: there should be substitution from (low-carbon) gas towards (high-carbon) oil, as the latter is found to be relatively more productive per unit of CO_2 emissions.

When the constraint is announced in advance (which for example was the case for the Kyoto Protocol), the extraction rate of the relatively more productive resource (in terms of GDP per unit of emissions) drops, while there is a rush on resources that will be used less after implementation. As a consequence the constrained period starts with (relatively) more of the productive resource, and resource owners of the other resource face a smaller loss (i.e. a smaller drop in scarcity rent), as compared to the situation without announcement. At the instant the constraint becomes binding the extraction rate of the productive input jumps up, and from then on relative extraction develops as would be the case with an unanticipated constraint.

Chapter 3: Announcement effects of climate policy

In chapter 3, we have a closer look a the effect of announcing climate policy in advance. We study the optimal paths of resource extraction and carbon dioxide emissions when the economy faces an announced constraint on emissions. Governments often announce policies some years in advance, partly to give firms time to adjust such that the real costs of the policy can be reduced. The Kyoto Protocol was agreed upon in December 1997, but the Protocol's first commitment period started only on January 1, 2008. Hence, agents were well in advance informed that it was likely that a policy on greenhouse gas emissions would enter into force at some future date. At the same time, agents were still free in their emissions in the period prior to 2008. We are especially interested in the answer to the following research question:

2. Can announced climate policy induce an increase in emissions?

As we are interested in emission levels instead of relative extraction paths, we include only one resource in our model. Our first result is that announcement of the policy indeed induces an *increase* in extraction and emissions at the instant of announcement. This is due to an *abundance effect*: as the entire resource stock must be extracted over time, if less is extracted during some period of time due to the constraint, more must be extracted over other periods. The question, then, is whether this additional extraction should be postponed, or should be brought forward to the period between announcement of the policy and its implementation. We show that it is optimal to do a bit of both (in order to keep discounted marginal utility constant over unconstrained times), and hence extraction and emissions jump up at the instant at which future climate policy is announced. As the idea underlying the policy is to stabilize the concentration of carbon dioxide in the atmosphere (Article 2 of the UNFCCC), this emissions increase goes directly *against* the spirit of the policy. Hence, there seems to be a trade-off between the economic gain of pre-announcement of climate policy, and the environmental loss coming from it.

In addition we show that, although emissions and extraction jump *up* at the instant of announcement of climate policy, both jump *down* at the instant of implementation. That is, even when climate policy is announced some years in advance, consumption will not be smoothed to avoid a jump in utility at the instant at which the constraint is put into practice. We also show that a longer interim period and a looser constraint reduce the sizes of both jumps. Furthermore, the length of the period in which the economy is constrained is shorter if the coefficient of relative risk aversion is higher, the interim period is longer, and the constraint is looser.

1.2.2 Part II of the thesis: Climate policy, input substitution, and technological change

In Part II of the thesis we study the relation between climate policy, input substitution and technological change. We first study how unilateral climate policy affects technological change and (directly and indirectly) carbon leakage (i.e. the emissions of countries that are not subject to climate policy). Finally, chapter 5 presents an empirical analysis of production functions, used in dynamic climate policy modeling, and links its results to the literature on climate policy and endogenous technological change.

Chapter 4: Carbon leakage revisited: unilateral climate policy with directed technical change

It is well-known among economists that when one country introduces climate policy in an attempt to reduce carbon dioxide emissions, other countries get incentives to increase their emissions. This is called carbon leakage. For example, when the production of energy-intensive goods is reduced in constrained countries due to the introduction of an emission constraint, the international prices of these goods will increase, giving unconstrained countries incentives to increase their production of energy-intensive goods and export them to constrained countries. In addition, reduced demand for fossil fuels from constrained countries reduces their prices, inducing unconstrained countries to substitute towards fossil fuels. Indeed, United States Senator Chuck Hagel (co-sponsor of the 1997 Byrd-Hagel Resolution, which states that the US Senate will not be a signatory to the Kyoto Protocol) argued that “The main effect of the assumed policy would be to redistribute output, employment, and emissions from participating to non-participating countries”.[12]

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[12] Remarks by Senator Hagel at "Countdown to Kyoto – International Conference on The Consequences of Mandatory Global CO_2 Emission Reductions", August 21, 1997 Canberra, Australia.

The price changes underlying possible channels of carbon leakage, however, also modify the incentives for innovation, changing the level and, most importantly, the direction of technological change (i.e. how technology levels develop across industries). Once the available technology changes as a result of climate policy, however, so do the responses of the unconstrained countries. The main research question of chapter 4 is therefore:

3. How does the introduction of directed technological change affect carbon leakage?

In this chapter, we study the consequences of induced (directed) technological change on carbon leakage using a stylized theoretical model of the interactions between constrained and unconstrained countries, which focuses on transmission mechanisms based on terms-of-trade effects. In order to be able to highlight the effects of induced technological change, we model two countries that are perfectly symmetric as refers to preferences, technology and endowments. In this way we rule out any other potential source of carbon leakage, which would cloud the effects of technological change. Indeed, we only allow the two countries to differ in one crucial respect: one country imposes a binding emission cap, while the other remains unconstrained. As the countries are symmetric before the imposition of the cap, the adjustment process represents a pure response to policy. In this sense, the paper analyzes a 'policy-induced pollution-haven effect'.

We show that, when (the composition of) technology is allowed to adjust endogenously, induced technological change always leads to a reduction in the degree of carbon leakage. As this technology channel of carbon leakage is not taken into account in the numerical literature on carbon leakage, the leakage rates (degree to which emission reductions are offset by increased emissions from unconstrained countries) that are estimated by this literature may be too high. In addition, we find that unconstrained countries might have incentives to reduce their emissions after the introduction of unilateral climate policy in other countries, when the elasticity of demand for carbon-based energy is sufficiently high. This would lead to a *negative* rate of carbon leakage.

Chapter 5: Production functions for climate policy modeling – an empirical analysis

In chapter 5 we have a look at the production functions that are used in dynamic climate policy models. These models generally use CES production functions with capital, labour and energy as inputs. Most models either first combine capital and labour in one CES function, and then combine this composite with energy in another CES function with a different value for the elasticity of substitution, or have all three inputs in a one-level CES function. Recent models in this literature introduce endogenous technological change, and study for example the effect of endogenous technological change on the costs of climate policy. A problem with this literature is that the values for the elasticities of substitution of the production function are not based on empirical estimates, while the values for these elasticities might affect the results with respect to the effects of endogenous technological change.

In this chapter, we estimate CES production functions with capital, labour and energy as inputs. The research questions are:

4. (a) Which nesting structure fits the data best?
   (b) How do the values for the elasticities used in the literature compare to the values we find?
   (c) How might the results of climate policy models with endogenous technological change be affected when using the elasticities found in this chapter?

We find that the (KL)E nesting structure, that is a nesting structure in which capital and labour are combined first, fits the data best, but we generally cannot reject that the production function has all inputs in one CES function (i.e. a 3-input 1-level CES function). These nesting structures are used by most of the recent models in the literature. However, for the (KL)E nesting structure we reject that elasticities are equal to 1, in favour of considerably lower values, while several of the climate policy models in the table use a Cobb-Douglas function for (part of the) production function. Finally we test for different technology trends and reject the hypothesis that only energy-specific technological change matters, and the hypothesis of input-neutral total factor productivity (TFP) growth, in favour of factor-specific technological change. That is, technology trends differ significantly between capital, labour and energy.[13]

Many of the recent models in the climate policy modeling literature use higher elasticities than those that we found in our empirical analysis. The higher an elasticity of substitution, the easier it is to substitute away from an input that faces an increase in its relative price, and the lower will be the need to invest in input-saving technological change. As a consequence, climate policy models that use

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[13] I distinguish between technological change and substitution purely from the abstract perspective of (CES) production functions: substitution takes place instantaneously and substitution possibilities are determined by a parameter called the elasticity of substitution (movements along a production isoquant), while technological change takes time and affects the (relative) marginal productivity of inputs even when their levels do not change (shifts of and changes in the shape of the isoquant). In reality, however, the line between substitution and technological change is thin. For more on this topic, see Sue Wing (2006).

elasticities of substitution that are too high may underestimate the role of endogenous technological change in reducing the costs of climate policy. Furthermore, energy-specific technological change and total factor productivity growth (even at the industry or country level) all take away degrees of freedom from an economy. Adding additional flexibility to a model could lead to a lower burden of climate policy on an economy.

1.2.3 Main findings of this thesis

This thesis shows that taking into account the dynamic aspects of climate policy may reverse conclusions found in static models. In general, we can divide our conclusions in good news and warnings for proponents of climate policy and policy makers. We begin with an overview of the good news.

Some good news...

The conclusions of chapters 4 and 5 provide some good news for the proponents of climate policy. In chapter 4 we find that carbon leakage may be smaller than has been thought so far. That is, the increase in emissions by countries without climate policy in response to the emission reduction by e.g. those countries that ratified the Kyoto Protocol may have been overestimated in the current quantitative literature on carbon leakage. We argue that the same price changes that cause leakage in the short-run, also affect incentives to innovate. This induced-technology effect works in the opposite direction, and tends to reduce the incentives for unconstrained countries to increase their emissions. Since energy in effect becomes scarcer due to the constraint on carbon dioxide emissions (that to a large extent result from energy production), it becomes attractive to innovate in technologies that increase the (marginal) productivity of energy. In equilibrium then, this increased productivity of energy leads to a higher price for energy for *both* the constrained and unconstrained countries, and hence to a reduction in energy use and emissions. Indeed, if the elasticity of relative demand for carbon-based energy is sufficiently large, unconstrained countries might even be induced to *reduce* their emissions, which goes against conclusions of static models.

In chapter 5 we have a look at the literature that studies the effect of endogenous technological change on the cost of climate policy. This literature argues that as climate policy affects prices of energy and fossil fuels, it will also affect the incentives to innovate (as we argue in chapter 4 as well). These new technologies might then in effect reduce the amount of emissions per unit of output, leading to lower costs of climate policy than when the role of technological change is not taken into account. Our empirical analysis in chapter 5 shows that many papers in this literature use elasticities of substitution in their production functions that have values that are too high. We argue that when this literature uses the lower elasticities that we find, their conclusions on the effect of endogenous technological change might change. To be more precise, when using lower elasticities, the incentive to innovate will be higher (as substitution possibilities are smaller), leading to more investment in new technologies, and hence a bigger effect of endogenous technological change on, and lower costs of, climate policy. Of course, with lower substitution elasticities, it will be harder to substitute away from energy, which might in turn lead to higher costs of climate policy. Which of these two effects dominates in the long run is an open question, and the answer will differ for each paper, as it depends on the initial values of the model's substitution elasticities.

...and some warnings.

Chapters 2 and 3 on the other hand provide some warnings for policy makers. In chapter 2 we study the optimal response of resource owners to a ceiling on carbon dioxide emissions, and argue that it might not be optimal to substitute from high-carbon resources to low-carbon resources. As it is not only carbon content that matters for the optimal response to climate policy, but also marginal productivity of the resources (determined by their scarcity), it is the productivity per unit carbon dioxide that matters. Our (preliminary) empirical analysis suggests that productivity per unit of carbon dioxide might be higher for oil than it is for gas. That is, it might be optimal to substitute from the low-carbon input gas to the high-carbon input oil, in response to climate policy. This counter-intuitive result has an important warning for policy makers: when fossil fuels are priced to their carbon content, supporting policies to move to a low-carbon economy (for example through subsidies on gas) might *increase* the costs of climate policy and increase the policy's burden on the economy. When carbon dioxide is properly priced, firms will decide which input gives them the highest level of output per unit of energy. Subsidizing a high-carbon input that effectively has a high productivity per unit of output induces firms to make use of less productive resources, which harms the economy.

In chapter 3 we study the announcement effects of climate policy. Governments usually announce climate policy some years in advance, partly to give firms time to adjust. As especially the power generation industry is facing fixed stocks of installed capital in coal and gas fired power plants, their scope to react to a limit in carbon dioxide emissions is limited. Giving firms time to prepare may lower the policy's burden on the economy. However, when taking into account the long-run dynamic aspects of climate policy, announcement of policy might be good for firms, but bad for the policy's target to reduce harmful emissions. As resource owners see their future prospects to sell their resource decline, they have incentives to lower the price and sell more of their resource in the period between announcement of the policy and the instant at which the policy becomes effective. Indeed, we show that announcement of the policy induces an *increase* in extraction and emissions at the instant of announcement. As the idea underlying the policy is to stabilize the concentration of greenhouse gases in the atmosphere (Article 2 of the UNFCCC), this emissions increase goes directly *against* the spirit of the policy. The key message of this chapter is that there is a trade-off between the economic gain from pre-announcing a ceiling on carbon dioxide emissions, and the environmental loss stemming from an increase in emissions in the period between announcement and implementation. The shorter the interim period, the larger will be the instantaneous effect. Of course, immediate implementation postpones emissions until the constraint ceases to be binding, which is the main purpose of climate policy. This lesson should be taken into account by countries that do not yet have a binding constraint on carbon dioxide emissions.

Part I

Climate policy and the optimal extraction of fossil fuels

CHAPTER 2

Climate policy and the optimal extraction of high- and low-carbon fossil fuels[14]

Climate change policies that call for a reduction in CO_2 emissions are likely to have an economy-wide impact by imposing significant cost on most sectors in the economy. Substitution from high-carbon to low-carbon energy sources may allow an economy to reduce carbon dioxide (CO_2) emissions at lower cost. For example, a country can build gas-fueled powerplants instead of coal-fueled powerplants. Or the country can expand sectors that rely on low-carbon inputs at the cost of sectors that mainly use high-carbon inputs. The overall cost of climate change policies therefore depends on the behaviour of both energy users and energy suppliers, and important questions in this context are: how should energy users substitute between different energy sources; should they make a transition towards a 'low-carbon economy'; how will resource rents for energy producing countries change; should they leave reserves of high-carbon resources (e.g. coal) unexploited, at least for a while?

In a standard static partial equilibrium setting, a CO_2 emission tax affects the user cost of high-carbon energy more than that of low-carbon energy and substitution will take place towards low-carbon energy. We show that in the more appropriate dynamic setting, with energy coming from non-renewable resource stocks, the results are quite different. Extending the canonical non-renewable resource model with a second resource, we find that a binding CO_2 emission constraint not nec-

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[14] This chapter is a slightly adjusted reprint of Smulders and van der Werf (2008). We thank Jean-Pierre Amigues, Geir Asheim, Rossella Bargiacchi, Corrado Di Maria, Christian Groth, Michel Moreaux, and Cees Withagen for useful discussions.

essarily calls for substitution towards low-carbon fuels in the short-run, but – depending on a well-defined measure of scarcity of the two resources – may instead call for relatively more intensive high-carbon fuel use in the short-run and less of it in the long-run.

Taking the current global policy regarding global warming as a starting point, we study how a permanent cap on carbon dioxide emissions ('Kyoto forever') affects the composition of energy use, the timing of extraction of different energy resources and their scarcity rents when the government uses a cost-effective instrument. We build a model that is as close as possible to the standard non-renewable resource model and distinguish between two non-renewable resources, for example coal and natural gas, that are imperfect substitutes in production and differ in CO_2 emissions per unit of effective energy.

We build our arguments on the fact that high-carbon and low-carbon inputs are imperfect substitutes at an aggregate level. Substitution between different types of products implies indirect substitution between energy types and types of fossil fuels. For example, a shift in the transport sector from road transport to rail implies a change in the fossil fuel mix as trucks use oil-based products while the rail sector uses electricity, which can be generated by gas-fueled powerplants. The energy sector can substitute between fossil fuel types when deciding upon investment in new powerplants: although for an individual power plant the choice between coal, oil, and gas is a discrete one, the point of indifference between the three inputs may differ at different locations, leading to imperfect substitution at the aggregate level.

We show that relative extraction in the constrained economy not only depends on the carbon content of the two inputs, but also on their relative productivity and physical scarcity. The best way to cope with an emission constraint is to intertemporally reallocate the extraction of the two given resource stocks such that production per unit of carbon dioxide emissions is relatively high at the time the emission constraint is binding, and low when the constraint no longer (or – in the case of an anticipated constraint – not yet) binds. Hence the constrained economy uses the resource with the lowest amount of emissions per unit of output relatively more intensively, as compared to an unconstrained economy. This resource is not necessarily the resource with lowest amount of carbon per unit of energy: because of diminishing returns to each of the energy inputs, the scarcer a resource relatively is, the higher its marginal productivity per unit of emissions.

Our empirical results suggest that it is cost-effective to substitute away from dirty coal to cleaner oil or gas. However, when it comes to choose between relatively clean natural gas and the dirtier input oil, the paradoxical "dirty-first result" might apply, i.e. there should be substitution from (low-carbon) gas towards (high-carbon) oil, as the latter is found to be relatively more productive per unit of CO_2

emissions.

The option of substituting low-carbon for high-carbon fuels to meet climate targets has been studied analytically in Chakravorty et al. (2008) and numerically in Chakravorty et al. (1997). The latter paper develops a numerical integrated assessment model with several non-renewables (oil, coal and natural gas), multiple energy demand sectors, and a clean renewable resource. The authors simulate three scenarios for technical change with optimal climate policy, but do not analytically identify the forces underlying relative extraction patterns. In Chakravorty et al. (2008), climate policy consists of an exogenous ceiling on the stock of pollution. A high- and a low-carbon fossil fuel, together with a clean backstop technology, are used in energy generation. The optimal order of extraction is studied. This work maintains the assumption that the fossil fuels are perfect substitutes, so that often one resource is exclusively used and at certain points in time there is a complete switch in resource use from one to the other fuel.

Most theoretical papers studying climate policy and fossil fuel extraction use a single (polluting) non-renewable resource. Withagen (1994) extends the standard Hotelling (1931) model with stock externalities from resource use and studies the optimal extraction path. Grimaud and Rougé (2005) treat pollution as a flow and extend the model with endogenous technological change and growth.

A second branch of theoretical papers has both a polluting non-renewable and a non-polluting backstop technology. Tahvonen (1997) extends Withagen's model with extraction costs and a backstop and shows that, if the initial stock of externalities is low enough, the extraction path of the non-renewable may have an inverted U-shape form. In a related paper, Chakravorty et al. (2006) study the effects of an exogenous ceiling on the stock of emissions on the use of the non-renewable resource and the backstop technology during and after the period that the constraint is binding.

Few papers study imperfect substitution between non-renewable resources. Exceptions are Beckmann (1974) and Hartwick (1978), but these early studies are not concerned with carbon emissions.

In the remainder of the chapter, we first present our model in section 2.1, and we study the economy without any form of climate policy in section 2.2. In section 2.3 we study an unexpected and initially binding constant CO_2 emission ceiling, and show that it might be optimal to use relatively more of the high-carbon input. In section 2.4 we study the empirical relevance of this paradoxical "dirty-first" result. Section 2.5 presents the effects of an announced constraint, and in section 2.6 we look at the robustness of our results with respect to alternative policies and technological change. We conclude in section 2.7.

2.1 The model

The representative consumer derives utility from final good Y and faces an intertemporal budget constraint: $\mathrm{d}V(t)/\mathrm{d}t = r(t)V(t) - Y(t)$. Here $V(t)$ is wealth and $r(t)$ is the market interest rate, at time t. The consumer maximizes intertemporal utility:

$$U(t) = \int_t^{\infty} \ln Y(\tau) \cdot e^{-\rho\tau} \mathrm{d}\tau, \tag{2.1}$$

where ρ is the utility discount rate. Maximizing (2.1) subject to the intertemporal budget constraint implies the following Ramsey rule:

$$\widehat{Y}(t) = r(t) - \rho. \tag{2.2}$$

where, as in the remainder of this chapter, the hat denotes the growth rate ($\widehat{Y} = \mathrm{d}\ln Y/\mathrm{d}t$).

The competitive final goods industry produces Y from two fossil fuel inputs, H and L, both scaled to units of energy, according to the following constant returns to scale CES technology (we suppress the time argument when no confusion arises):

$$Y = A\left(\eta_H R_H^{\frac{\sigma-1}{\sigma}} + \eta_L R_L^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{2.3}$$

where A is the level of total factor productivity, R_i is the amount extracted of resource $i \in \{H, L\}$, η_H and η_L are positive technology parameters and $\sigma \in (0, \infty)$ is the constant elasticity of substitution. The use of fossil fuels causes emissions of carbon dioxide. The two inputs differ in their CO_2 emission intensity per unit of energy and we denote the (constant) CO_2 emission coefficients of H and L by ε_H and ε_L respectively, with $\varepsilon_H > \varepsilon_L$ so that H is the relatively dirty or high-carbon input. The total amount of emissions is denoted by Z.[15] If the economy is subject to an emissions constraint, total emissions cannot exceed a maximally allowed amount $\bar{Z}$, according to the following constraint:

$$\varepsilon_H R_H(t) + \varepsilon_L R_L(t) = Z(t) \le \bar{Z}. \tag{2.4}$$

As we are interested in the reaction of the economy to the constraint rather than in optimal climate policy itself, we assume that the constraint $\bar{Z}$ is exogenous. The government allocates tradable emission permits over producers in the final goods industry, who trade them at a market price p_Z and buy resources of type i at price

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[15] Our notation is consistent with the measurement of R_i in units of energy and Z in units of carbon. By rescaling R_i and Z it is possible to normalize - without loss of generality - three of the four parameters ε_L, ε_H, η_L, and η_H, to unity. However, to facilitate interpretation and comparison to the data, we do not apply this normalisation.

p_{Ri}.[16] The price of the final good is normalized to one for every period. Firms maximize profits and the first order conditions for resource use read (from (2.3) and (2.4)):

$$A^{\frac{\sigma-1}{\sigma}}\eta_i\left(\frac{Y}{R_i}\right)^{\frac{1}{\sigma}} = p_{Ri} + \varepsilon_i p_Z. \tag{2.5}$$

This equation states that the marginal revenue from resource input i (the marginal product at the left-hand side) equals its marginal cost (the user price at the right-hand side), which consists of the price of the resource augmented with the cost of pollution in case the constraint is binding.[17]

The two fossil fuels are extracted from stocks of non-renewable resources, S_H and S_L respectively, according to

$$\mathrm{d}S_i/\mathrm{d}t = -R_i, \tag{2.6}$$
$$\int_0^\infty R_i \mathrm{d}t \leq S_{i0},$$

where S_{i0} is the initial stock of resource i. The transversality condition reads:

$$\lim_{t\to\infty} p_{Ri}(t)S_i(t) = 0.$$

Resource owners maximize the net present value of profits from exploiting the non-renewable resource stocks, taking resource price p_{Ri} as given. Extraction costs are assumed to be zero so the resource price is a pure scarcity rent. For each of the resources this results in the familiar Hotelling rule:

$$\widehat{p}_{Ri}(t) = r(t). \tag{2.7}$$

From this we see that the relative resource rent p_{RH}/p_{RL} will be constant over time, as both rents grow at the same rate.

We are now ready to study extraction of the two resources. We first study extraction in an economy without a CO_2 emission constraint and then move to a constrained but otherwise identical economy.

2.2 The economy without (the prospect of) climate policy

Suppose that from some instant T (possibly equal to 0) on the economy is unconstrained and does not expect future climate policy. In this case the economy is

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[16] Although we present the results for the decentralized economy with regulation through tradable pollution permits, it can be shown that a planner who maximizes utility subject to the exogenous emission constraint chooses exactly the same allocation. Hence, the setting we study is one of cost-effective environmental regulation.

[17] Note that we will always have an interior solution. If $R_i = 0$ we would have $Y = 0$ for $\sigma \leq 1$, while $\partial Y/\partial R_i = A^{\frac{\sigma-1}{\sigma}}\eta_i (Y/R_i)^{1/\sigma} \to \infty$ for $\sigma > 1$ which violates (2.5) for finite p_{Ri} and p_Z.

described by a pure depletion or cake eating model from $t = T$ on (see e.g. Heal, 1993). Time differentiating (2.5) (with $p_Z = 0$) and substituting (2.7), we find that both inputs grow at the same rate. Combining the results with (2.3), we find that the two scarcity rents grow at rate $\widehat{p_{Ri}} = r = \widehat{A}$. Finally, substituting (2.2), we find that extraction and emissions decrease at a rate equal to the utility discount rate:

$$\widehat{R}_H = \widehat{R}_L = -\rho \ \forall \ t \geq T, \tag{2.8}$$

After integrating (2.8) and imposing the constraint that forward-looking resource owners anticipate that eventually all reserves will be sold, we find that the extraction rates of the two resources can be expressed as:

$$R_i(t) = \rho S_i(t) \ \forall \ t \geq T. \tag{2.9}$$

Consequently total emissions equal

$$Z(t) = \rho \cdot (\varepsilon_H S_H(t) + \varepsilon_L S_L(t)) \ \forall \ t \geq T \tag{2.10}$$

(see (2.4)). According to (2.8) and (2.9), relative extraction is constant over time and equal to instant T's relative stock:

$$\frac{R_H(t)}{R_L(t)} = \frac{S_H(T)}{S_L(T)} \ \forall \ t \geq T. \tag{2.11}$$

From the first order conditions (2.5) and equilibrium relative extraction (2.11) we find the equilibrium relative scarcity rent:

$$\frac{p_{RH}(t)}{p_{RL}(t)} = \frac{\eta_H}{\eta_L}\left(\frac{S_H(T)}{S_L(T)}\right)^{-1/\sigma} \ \forall \ t. \tag{2.12}$$

These results reveal that as long as the economy is unconstrained and does not expect future climate policy, relative extraction in the unconstrained economy is constant and equals relative stocks at each point in time. Since conservation of both resource stocks requires that resource owners earn the same return on the two resources, both resource prices grow at the common rate r in equilibrium. Hence, the relative price is constant over time and the constant-returns-to-scale production function then implies that relative demand is constant as well. As resource owners want to fully exploit the available reserves, from (2.1) and (2.7), stock dynamics require relative extraction to equal relative stocks which implies that the initial relative scarcity rent in an unconstrained economy is determined by initial availability of the resources.

2.3 An unexpected emission constraint

We now introduce the constraint on emissions. The constraint is unexpectedly introduced at time $t = 0$ and is binding by then. It will stay at the level $\bar{Z}$ forever, which is known by all agents. The constraint will not bind forever, though, since resource stocks, from which emissions stem, are depleted over time (cf. (2.10)). In particular, we derive the following result:

Lemma 2.1. *Define T as the instant from which onward emissions cease to be constrained. If constraint $\bar{Z}$ is introduced unexpectedly at $t = 0$, then:*

$$T = \frac{\varepsilon_H S_{H0} + \varepsilon_L S_{L0}}{\bar{Z}} - \frac{1}{\rho}. \tag{2.13}$$

Proof. The total amount of CO_2 that will be emitted from $t = 0$ on can be written as $\varepsilon_H S_{H0} + \varepsilon_L S_{L0} = [\varepsilon_H (S_{H0} - S_H(T)) + \varepsilon_L (S_{L0} - S_L(T))] + [\varepsilon_H S_H(T) + \varepsilon_L S_L(T)]$. The first term in square brackets represents total emissions in the period that the economy is constrained, so this term equals $T\bar{Z}$. For any $t \geq T$, we can use (2.4) and (2.9), from which we find that the second term in square brackets equals $\bar{Z}/\rho$. Combining results, we find (2.13). □

Clearly, a larger initial stock or a stricter environmental policy implies a longer period of being restricted. A lower discount rate, and hence more patient consumers, implies that the economy is suffering the constraint for a shorter period as the economy tends to extract and pollute less (see (2.10)).

To meet the emissions constraint, (2.4), resource use can be reduced equi-proportionally, or its composition can be changed (relative to the period before $t = 0$). In the latter case, emissions per unit of output will change:

Lemma 2.2. *Define $\bar{S} \equiv (\eta_H \varepsilon_L / \eta_L \varepsilon_H)^{\sigma}$. Emissions intensity Z/Y reaches a minimum for $R_H/R_L = \bar{S}$ and increases in $|R_H/R_L - \bar{S}|$.*

Proof. From (2.3) and (2.4) we find that Z/Y is a function of R_H/R_L only. Taking the first order derivative $\mathrm{d}(Z/Y)/\mathrm{d}(R_H/R_L)$, we find the result. □

Because of imperfect substitutability, a very high or very low level of one of the resource inputs – while still meeting the emission constraint – results in relatively little output and a high emission intensity. The more polluting one input relatively is (as indicated by a relatively large ε_i), the less intensively this input must be used should one want to minimize emissions intensity. Similarly, if one input is much more productive than the other one (as indicated by the η_i's), intensive use of this input results in relatively high output and low emission intensity.

In equilibrium, the development of relative extraction in the constrained economy with an unannounced emission constraint can be summarized by the following proposition:

Proposition 2.1. *Suppose a CO_2 emission constraint is unexpectedly introduced. Then*

1. *if the high-carbon input (low-carbon input) is relatively scarce, that is if $S_{H0}/S_{L0} < (>) \bar{S}$,*
   (a) *the relative scarcity rent p_{RH}/p_{RL} jumps up (down) on impact;*
   (b) *relative extraction R_H/R_L jumps up (down) on impact, but decreases (increases) over time as long as the economy is constrained;*
   (c) *relative extraction stays above (below) the level of the relative stocks S_H/S_L as long as the economy is constrained, but equals relative stocks when the constraint ceases to be binding;*
   (d) *the high-carbon resource stock declines faster (less fast) than the low-carbon resource stock as long as the economy is constrained;*
2. *if the high- and low-carbon input are equally scarce (that is, if $S_{H0}/S_{L0} = \bar{S}$), the relative scarcity rent, relative extraction and relative stocks do not change after the imposition of the emission constraint;*
3. *if the two inputs are* not *equally scarce, emissions per unit of output jump down but increase over time to a higher level compared to the period before the constraint was imposed; they remain constant after the constraint ceases to be binding.*

Proof. See appendix 2.A. □

The proposition states that at the instant on which emissions become unexpectedly constrained, substitution takes place towards the relatively scarce input, that is towards input i for which $S_{i0}/S_{j0} < \bar{S}$, where $\bar{S} \equiv (\eta_H \varepsilon_L / \eta_L \varepsilon_H)^{\sigma}$ see lemma 2.2. The increase in the relative use of the scarce input implies that over time this input will become even scarcer, since the relative stock S_i/S_j decreases over time (part 1(d) of the proposition). This explains the jump in the relative scarcity rent (part 1(a) of the proposition).

We illustrate the paths of extraction, for the case in which $S_{H0}/S_{L0} < \bar{S}$, by the thick arrows in Figure 2.1. The constrained economy moves along line $\bar{Z}$, at which emissions are at the imposed ceiling and which is defined by $R_H = (\bar{Z} - \varepsilon_L R_L)/\varepsilon_H$. Since over time the economy moves to lower production isoquants, pollution per unit of

GDP gradually increases over time. The unconstrained economy, which according to (2.9) extracts a constant fraction of each available stock, moves down along a ray from the origin with slope S_{H0}/S_{L0}.

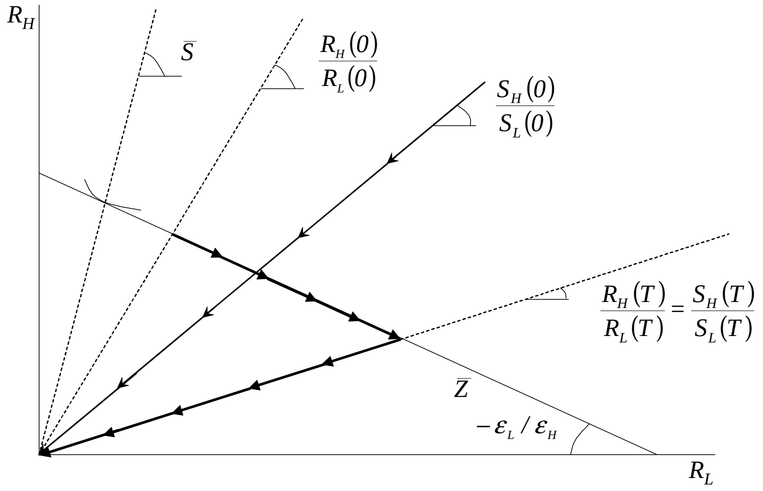

Figure 2.1: Extraction paths for $S_H(0)/S_L(0) < \bar{S}$: the unconstrained economy (thin arrows) and the economy with an unannounced constraint (thick arrows)

Two basic forces drive the evolution of relative energy use: physical scarcity and marginal productivity per unit of pollution. The emission constraint induces the economy to save on pollution per unit of GDP. If relative energy use, R_H/R_L, was equal to $\bar{S}$, output per unit of emissions would be maximized; the closer relative use approaches $\bar{S}$, the higher output per unit of emissions. As the unconstrained economy aligns relative resource use with resource supply, as measured by relative stocks, it uses relatively little of the relatively scarce resource, while this resource might have the highest marginal product per unit of CO_2. Once the constraint is imposed, the economy starts to use more of the resource that has highest marginal productivity per unit of pollution, and hence relative extraction jumps closer to $\bar{S}$. However, relative use cannot deviate too much from relative stocks, since at the time the constraint no longer binds (time T), relative resource use and available stocks have to be aligned again. Therefore the pollution constraint makes the economy intertemporally reallocate the extraction of resources, such that output per unit of pollution is high when the pollution constraint is most binding, and then gradually substitutes towards the resource with lower productivity per unit of pollution as the constraint becomes less binding. Eventually, once the constraint does not bind anymore, the economy smoothly ends up at the point where resource use and supply are aligned.

The implication is that the high-carbon input might be used intensively first. This "dirty-first result" arises when the high-carbon resource is physically relatively scarce, such that resource use in line with relative stocks implies that the high-carbon input has higher productivity per unit of CO_2. For future reference it is useful to formalize this "dirty-first condition" as:

$$\frac{S_{H0}}{S_{L0}} < \left(\frac{\eta_H/\eta_L}{\varepsilon_H/\varepsilon_L}\right)^{\sigma} \equiv \bar{S}. \tag{2.14}$$

To further explain why relative resource use changes over time and intertemporal substitution between high- and low-carbon resources takes place in the constrained economy, we divide (2.5) for the low-carbon input by that for the high-carbon input and rewrite the result, to derive the following expression:

$$\frac{\eta_H}{\eta_L}\left(\frac{R_H}{R_L}\right)^{-1/\sigma} = (1-\zeta)\frac{p_{RH}}{p_{RL}} + \zeta\frac{\varepsilon_H}{\varepsilon_L}, \tag{2.15}$$

where $\zeta = p_Z\varepsilon_L/(p_{RL}+p_Z\varepsilon_L)$ is the share of pollution costs in the user price of low-carbon resources. This equation reveals that relative demand for energy sources depends on the relative user price, which is a weighted average of relative scarcity rents and relative pollution costs. Relative scarcity rents (p_{RH}/p_{RL}) and pollution costs ($\varepsilon_H/\varepsilon_L$) are constant over time (see (2.12)). However, the share of pollution cost in the user price ζ gradually falls, since scarcity rents increase and the price of pollution permits falls. As a result, the relative user price of high-carbon resources changes over time, thus inducing intertemporal substitution.

Whether the relative user price rises or falls depends on the sign of $\varepsilon_H/\varepsilon_L - p_{RH}/p_{RL}$ (see (2.15)). If $\varepsilon_H/\varepsilon_L < p_{RH}/p_{RL}$, the relative user price of high-carbon resources increases over time. Intuitively, with this inequality the high-carbon resource is relatively costly mainly because of scarcity cost rather than pollution cost, and this resource benefits the least from lower pollution costs. Users then gradually substitute towards the low-carbon resource during the period that the emissions constraint is binding. This case arises if the inequality in (2.14) is satisfied.[18] In the opposite situation, with $\varepsilon_H/\varepsilon_L > p_{RH}/p_{RL}$ and (2.14) holding with reverse inequality, the high-carbon resource mainly benefits from pollution price reductions and users gradually substitute to the high-carbon resource.

We conclude this section by a comparative static result. As climate change agreements typically specify fixed-term installments of pollution reduction and are subject to renegotiation, it is relevant to study the effects of a change in the stringency of the pollution cap. If the emission constraint becomes tighter, pollution costs

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[18] If $S_{H0}/S_{L0} < \bar{S}$, we have $R_H/R_L < \bar{S}$, from (2.22) in the appendix, and then $\varepsilon_H/\varepsilon_L < p_{RH}/p_{RL}$, from (2.23).

become a more important determinant in the cost of resource use as compared to scarcity rents, ceteris paribus. As a consequence the relative extraction rate jumps closer towards $\bar{S}$ (where $\bar{S}$ is the level that would apply if scarcity did not matter), as is stated by the following proposition:

Proposition 2.2. *Suppose a binding CO_2 constraint is unexpectedly further tightened, and let input i be the relatively scarce input: $S_{i0}/S_{j0} < (\eta_i\varepsilon_j/\eta_j\varepsilon_i)^{\sigma}$. Then, compared to the case with the initial (looser) constraint,*

1. *the economy is constrained for a longer period;*
2. *relative extraction jumps further towards the relatively scarce input;*
3. *S_i/S_j is lower at the instant the constraint ceases to be binding, and hence relative extraction R_i/R_j will be lower when unconstrained;*
4. *the relative scarcity rent p_{Ri}/p_{Rj} jumps further upwards;*
5. *the carbon-intensity of output jumps further downwards.*

Proof. See appendix 2.A. □

With a more stringent constraint, fewer resources can be extracted so that it takes longer before unconstrained emissions are below the level of the ceiling and the economy is constrained for a longer period. Furthermore, the tighter constraint induces the economy to further increase the productivity per unit of emissions. The resulting relative extraction rate and relative resource rent are closer to the level (viz. $\bar{S}$) that would apply in an economy in which pollution only (rather than scarcity) would matter.

2.4 The empirical relevance of the “dirty-first condition”

The necessary condition for the relative use of high-carbon inputs to go up (our "dirty-first result") is, as given in inequality condition (2.14), that the high-carbon input is relatively scarce in a physical sense, but relatively productive in terms of its marginal contribution to output per unit of CO_2 emissions. We now want to explore whether this inequality could hold in reality. We use data on prices, consumption, and stocks of coal, oil and gas, for the period 1984-2005 (1987-2005 for coal due to availability of data on coal prices), to see for which fuels the inequality (2.14) holds.[19]

Productivity parameters η_i in (2.14) cannot be directly observed, but can be derived from observed equilibrium prices and quantities: assuming the data reflect a zero pollution tax and using the firms' optimality conditions (2.5) (with $p_Z = 0$) to eliminate η_i, we can rewrite (2.14) as

$$\frac{S_H(t)}{S_L(t)} < \frac{R_H(t)}{R_L(t)} \left(\frac{p_{RH}(t)/\varepsilon_H}{p_{RL}(t)/\varepsilon_L} \right)^{\sigma}. \tag{2.16}$$

A first look at the data shows that roughly the following relations hold: $S_{coal}(t) \gg S_{oil}(t) \approx S_{gas}(t)$; $R_{oil}(t) \gg R_{coal}(t) > R_{gas}(t)$; $p_{oil}(t)/\varepsilon_{oil} \approx p_{gas}(t)/\varepsilon_{gas} > p_{coal}(t)/\varepsilon_{coal}$. First we consider the combination with $H = coal$ and $L = oil$: the left-hand side of the inequality in (2.39) exceeds unity and the right-hand side is smaller than unity (for any $\sigma \geq 0$). Hence, the inequality (the "dirty-first condition") does not hold and we conclude that, according to the data, climate policy will induce substitution from high-carbon coal to low-carbon oil. If we make the same comparison for $H = coal$ and $L = gas$, we see that with $\sigma \geq 0$ the inequality is again likely to be violated. Hence the data suggest that, after the introduction of a ceiling on the amount of CO_2 emitted, there will be substitution from high-carbon coal towards low-carbon gas. With $H = oil$ and $L = gas$, however, the inequality in (2.39) is likely to hold. That is, the data suggest that climate policy induces substitution from low-carbon gas to high-carbon oil.

In the next step, we looked at the inequality in (2.39) for individual years. With a production function with coal and oil as inputs, we then find that the inequality is indeed violated for any $\sigma \geq 0$, for all years, and the pattern of substitution is towards the low-carbon input oil. The same result holds when $H = coal$ and $L = gas$: climate policy induces substitution from high-carbon input coal towards the low-carbon input gas. However, when $H = oil$ and $L = gas$, the results are indecisive. For 11 out of our 22 observations we find that the result depends on the size of σ, while for the other half of our observations the inequality holds for any $\sigma \geq 0$ (hence substitution towards the high-carbon input). In the former case the inequality holds for values of σ that are not too large, where the critical value of σ ranges from 0.6 to 17.5.

As a final exploration, we used our data to estimate the elasticity of substitution between oil and gas. We used both country-level panel data and world-level time series data to estimate productivity parameters and both short-run and long-run

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[19] We used data from the 2006 BP Statistical Review of World Energy, available at http://www.bp.com/statisticalreview. We converted all data in Million Tonnes of Oil Equivalents. We use relative emission coefficients that are compatible with US and German data. Appendix 2.B contains further details on data collection, the calibration, and regressions.

elasticities of substitution. All regressions that report a positive value for the elasticity of substitution, and for which we cannot reject the null hypothesis of no autocorrelation, report an elasticity of substitution between oil and gas that is sufficiently low for the inequality in (2.39) to hold. Hence, the regressions suggest that, following from Proposition 2.1, with a ceiling on carbon dioxide emissions, it is optimal to substitute from low-carbon gas towards high-carbon oil.

In sum: Our data suggest that both oil and gas are more productive per unit of CO_2 than scarce, relative to coal, and hence climate policy is likely to induce substitution from the high-carbon fuel coal to the low(er)-carbon inputs oil and gas. However, according to our data the marginal productivity of carbon coming from the use of oil is higher than the marginal productivity of carbon coming from gas, while the two resources are roughly equally scarce in a physical sense. As our theory suggests, this would make it optimal to substitute from gas towards oil when climate policy constrains CO_2 emissions, and the "dirty-first result" might be of more than just theoretical interest.

2.5 Announcement effects

We now investigate how the economy reacts to an emission constraint in the case that agents anticipate the actual implementation of the policy.[20] In particular, we study the path of resource extraction for the situation in which the carbon constraint starts to be effective at time $t_K > 0$, but is announced at time $t = 0$, so that preparations can be made over the period $t \in (0, t_K)$. In chapter 3 we have a closer look at the effects of an announced emission constraint, but then we focus on the path of emissions after announcement, and restrict ourselves to the case of only one fossil fuel.

Agents maximize the same objective functions subject to the same constraints as in the previous section, with the only difference that the constraint (2.4) is now binding from $t = t_K$ instead of $t = 0$. The resulting path of relative extraction can be characterized by the following proposition:

Proposition 2.3. *Suppose a CO_2 emission constraint is announced before it is actually implemented. Then,*

1. *if* $S_{H0}/S_{L0} < (>) \bar{S}$,

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[20] Kennedy (2002) also studies the effect of an announced emission constraint. Using a two-period model without resources he shows that it may be optimal for a small country to reduce emissions before the 2008-2012 commitment period, either because of co-benefits (e.g. reductions in emissions of other pollutants than CO_2 that go together with a reduction in fossil fuel combustion) or because early investments in physical capital help reducing adjustment costs.

   (a) *relative extraction* R_H/R_L *(i) jumps down (up) at the announcement, (ii) stays constant until actual implementation, (iii) jumps up (down) at actual implementation and (iv) gradually declines (increases) until the pollution constraint ceases to be binding, attaining the level it had before implementation;*
   (b) *the high-carbon resource stock (i) gets depleted less fast (faster) than the low-carbon resource stock between announcement and start of implementation; (ii) the opposite happens when the pollution constraint is binding;*
   (c) *at the instant of implementation, emissions per unit of GDP jump down;*

2. *if* $S_{H0}/S_{L0} = \bar{S}$*, relative extraction, relative stocks, and emissions per unit of GDP remain constant forever;*

3. *at the instant of implementation, both output and emissions jump down.*

Proof. See appendix 2.A. □

The proposition implies that the announcement of an emission constraint at a future date immediately causes a drop in the rate of extraction of the relatively more productive resource (in terms of GDP per unit of emissions) and a rush on resources that will be used less after implementation. As a consequence the constrained period starts with (relatively) more of the productive resource, and resource owners of the other resource face a smaller loss (i.e. a smaller drop in scarcity rent), as compared to the situation without announcement. At the instant the constraint becomes binding the extraction rate of the productive input jumps up, and from then on relative extraction develops as would be the case with an unanticipated constraint.

We illustrate the extraction paths for the case where $S_{H0}/S_{L0} < \bar{S}$ in Figure 2.2 by the thick arrows. For the same case, Figure 2.3 illustrates the development of relative extraction and relative stocks over time. Initially relative extraction is below relative stocks, causing an increase in the latter, while after the introduction of the constraint relative extraction jumps up to a level higher than that of the relative stocks, and hence the latter decline until relative extraction and relative stocks are equal at the instant that the constraint ceases to be binding (part 1 of proposition 3).

At the time the constraint is implemented, the economy substitutes towards the more productive resource, in terms of GDP per unit of CO_2). As a consequence, the economy's pollution intensity Z/Y decreases. Since the introduction of the constraint is expected and fully anticipated, the period between announcement and implementation is used to intertemporally shift resource extraction in order to mitigate the fall in production at the time of implementation.

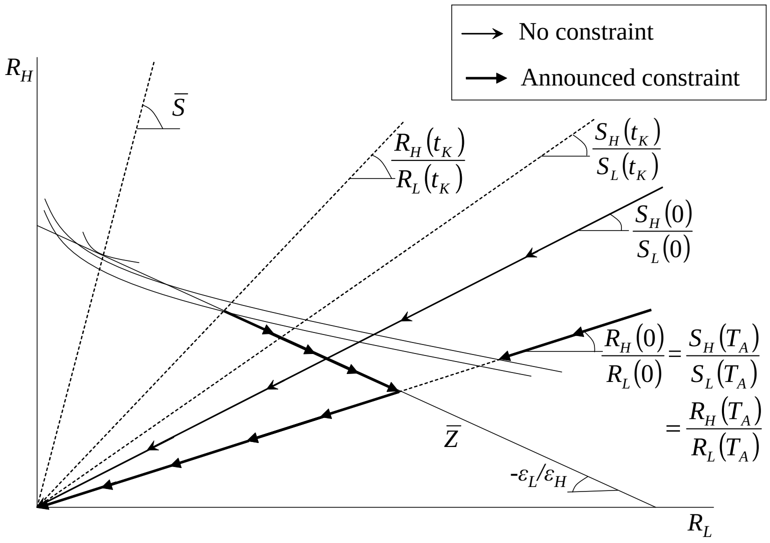

Figure 2.2: Extraction paths for $S_H(0)/S_L(0) < \bar{S}$: the unconstrained economy (thin arrows) and the economy with an announced constraint (thick arrows)

2.6 Alternative policies and technical change

In this section we check whether our results, and particularly the possibility of a “dirty-first” result, are robust with respect to alternative policies (a stock constraint and an emission intensity constraint) and to the introduction of technological change in the model.

2.6.1 Stock and emission intensity constraints

The emissions reduction policy studied so far constrained the flow of pollution, as the simplest interpretation of the Kyoto protocol. However, it is widely recognized that not the flow but the stock of cumulative emissions, or CO_2 concentration levels, should be the criterion of sound climate change policy. Moreover, even a flow constraint can be combined with a flexibility provision that firms could “bank” emission permits, allowing them to keep permits for later use or borrow against the future. To check how our results could change with an emissions concentration target or banking policy, we study how a permanent constraint on cumulative emissions affects relative extraction of high- and low-carbon resources.

We denote cumulative emissions by X, so that $\dot{X} = Z$. The policy that is announced and implemented at time zero caps cumulative emissions, $X(t) \leq \bar{X}$, at any point in time. The amount of pollution permits introduced at time 0 in the market equals $\bar{X} - X(0) > 0$; the permits are bankable and tradable. We assume that the constraint

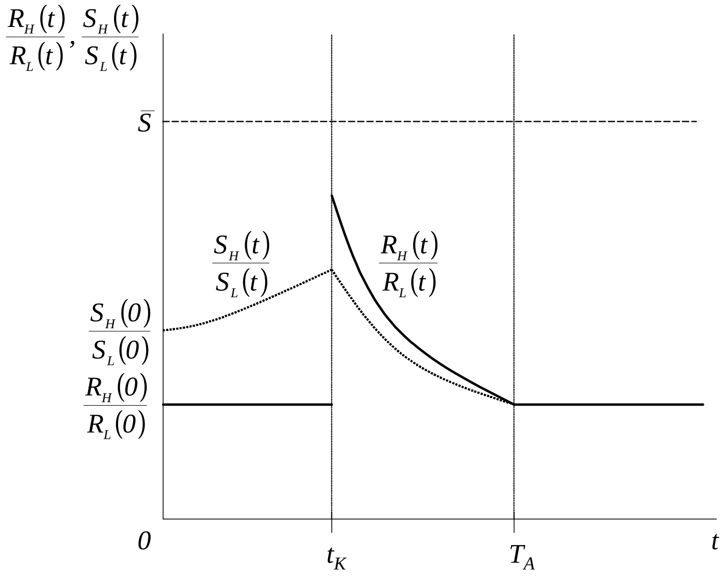

Figure 2.3: Development of relative extraction (solid lines) and relative stocks (dotted line) with announced constraint, for $S_H(0)/S_L(0) < \bar{S}$

is binding at introduction, which requires that cumulative pollution from unconstrained resource use exceeds the amount of permits, i.e. $X(0)+\varepsilon_H S_H(0)+\varepsilon_L S_L(0) \geq \bar{X}$.

Each unit of CO_2 emissions reduces the remaining stock of permits. Hence, the stock of permits is like a non-renewable resource and the permit price, p_Z, must grow at rate r to make owners of permits indifferent between selling now or selling in future. Now the users of permits, the producers, face resource price as well as pollution prices growing at the same rate r, so that the user price, at the right-hand side of first-order condition (2.5), grow at rate r as well and the relative user price of the two resources stays constant over time. Hence, while the flow constraint induced substitution over time, the stock constraint fixes relative resource use over time. The question now is whether the relative use of high-carbon inputs could be higher under the stock constraint than in the unconstrained economy, in which case we would find again the “dirty-first result”.

With both resource inputs growing at the same rate, we find – as demonstrated already above for the unconstrained economy – that $\widehat{R_H} = \widehat{R_L} = \widehat{Y} - \widehat{A} = (r-\rho) - r = -\rho$ so that cumulative extraction of resource i and cumulative pollution from resource i after $t = 0$ equal $R_i(0)/\rho$ and $\varepsilon_i R_i(0)/\rho$, respectively. In addition, relative resource extraction R_H/R_L is constant over time, even though the economy is constrained. The market sector now chooses levels of resource inputs so as to maximize net present value of output under the constraints that cumulative extraction does not exceed available resources, and cumulative pollution equals available emissions permits. Using our solutions for the growth rates of resource input and interest rate, we can write the maximization problem as a static one (at time $t = 0$; we omit this time indicator):

$$\text{Max. } AF(R_H, R_L)/\rho, \text{ s.t. } R_i \leq \rho S_i, \sum_i \varepsilon_i R_i = \rho\left(\bar{X} - X\right) \tag{2.17}$$

where $F(.)$ is the CES function in (2.3). From the solution of (2.17) we derive the following:

Proposition 2.4. *Suppose a binding stock constraint is unexpectedly introduced. Then*

1. *relative extraction R_H/R_L jumps up (down) if $S_{H0}/S_{L0} < (>)\bar{S}$, and*
2. *leaves relative extraction unaffected if $S_{H0}/S_{L0} = \bar{S}$.*

Proof. See appendix 2.A. □

Hence, under exactly the same conditions as under the flow constraint, $S_{H0}/S_{L0} < \bar{S}$, also the stock constraint induces the economy to use relatively more of dirty input.

Note that a constraint on cumulative emissions is not equivalent to an emissions concentration target, since it abstracts from decay of the emissions stock in the atmosphere that comes from ocean CO_2 uptake and other carbon sinks. If we model the change in CO_2 concentrations, C, in the simplest possible way as the balance between emissions and proportional decay, viz. $\dot{C} = Z - \delta C$, and assume a policy that caps emissions forever by imposing $C(t) \leq \bar{C}$, the equilibrium path for relative extraction has features of both the stock-constraint path and the flow-constraint path. Initially, $C(t) < \bar{C}$, so the concentration level can increase but a rising pollution price reflects that the ceiling is being approached, like in the stock constraint case. Once concentrations hit the ceiling, the flow of pollution is restricted to total decay $\left(Z = \delta\bar{C}\right)$ until resource stocks are so small that unrestricted resource use results in low pollution levels and declining concentrations $\left(Z = \rho\sum_i \varepsilon_i S_i < \delta\bar{C}\right)$, like in the flow constraint case. Again, the dirty-first result will appear for $S_{H0}/S_{L0} < \bar{S}$.

As an alternative route to mitigate climate change, one that is claimed to be politically more attractive, there have been proposals to set targets for emissions intensity (in particular in the USA when it voted down the Kyoto Protocol and in Canada recently). In our model this implies an upper bound on Z/Y. Recall that $R_H/R_L = \bar{S}$ minimizes Z/Y and that, because of the linear homogeneity of the production function, Z/Y increases with $|R_H/R_L - \bar{S}|$. Hence, the equilibrium relative extraction rate must be close enough to $\bar{S}$ under an intensity constraint. Starting from an unconstrained equilibrium in which high-carbon inputs have the highest productivity per unit of CO_2 $\left(S_{H0}/S_{L0} < \bar{S}\right)$, the economy will satisfy a (binding) intensity constraint by increasing relative high-carbon use. Hence, our dirty-first result shows up under the same conditions as with flow or stock constraint.

In sum, we find that however pollution is constrained (as a flow, stock, atmospheric concentration, or per unit of GDP alike), the economy starts using more of the resource input that has the highest marginal productivity per unit of pollution. This input is the one with high CO_2 emissions per unit of energy if its physical scarcity (relative to productivity) forces unconstrained use of it to be small (i.e. if $S_{H0}/S_{L0} < \bar{S}$).

2.6.2 Technological change

One could wonder whether technological change affects the "dirty-first" result that it might be optimal to substitute towards the high-carbon input, after the introduction of climate policy. While we saw that neutral technological change, $\widehat{A}$, has no impact on the relative use of the two resources, this changes with non-neutral or biased technical change, to be modeled by different rates of increase in η_H and η_L. An increase in η_H/η_L implies an increase in the cost-share of the dirty input, i.e. dirty-input-using technological change: the prospect of higher relative productivity of the high-carbon input in the future induces users to postpone use of this resource. Compared to the situation with neutral technological change, dirty-input-using technological change would shift the use of the high carbon input to the future and would partly offset any dirty-first effect of a emissions constraint. However, if technological change has a high-carbon-saving bias (causing η_H/η_L to decrease), the opposite would happen: frontloading of the high-carbon input, as compared to the neutral technological change case, and reinforcing any dirty-first result.

The interesting question is therefore whether high-carbon-using (i.e. an increase in η_H/η_L) or high-carbon-saving technological change is the likely equilibrium outcome after the introduction of climate policy. To answer this question we need a model of endogenous innovation, for example along the lines of the model of directed technological change by Acemoglu (2002). Although the full development of such a model is left for future research, we can try to use the following general insight from Acemoglu's model without natural resources: when the use of factor x increases relative to factor y, innovation tends to be factor-x using (see also Di Maria and Smulders, 2004). This suggests that if users tend to shift to high-carbon inputs in immediate reaction to the emissions constraint (our dirty-first result), innovation becomes high-carbon-using. However, later on relative use of the high-carbon input must be necessarily lower than without the emissions constraint, which will trigger high-carbon-saving technological change. As a result, the productivity of the high-carbon input will be higher especially in the medium-run, but not in the short-run (innovation takes time) and not in the long-run, when innovation becomes pollution-saving (all in comparison to the unconstrained case). The optimal reaction is then to concentrate extraction and use of the high-carbon resource in the medium-run, rather than the short-run and the long-run, as compared to the case without endogenous biased technological change. We therefore expect that endogenous technological change mitigates the reaction of relative extraction to the emissions constraint (R_H/R_L stays closer to the unconstrained level), but that the direction of the change in relative use as well as the conditions for a dirty-first result are not affected.

2.7 Concluding remarks

In reaction to a ceiling on the amount of carbon dioxide emissions an economy may want to substitute between high-carbon and low-carbon fuels. We have shown that in the standard Hotelling model extended with a second, imperfectly substitutable resource, the economy optimally decreases CO_2 intensity of GDP. However, this is not always obtained through substitution of low-carbon for high-carbon inputs (e.g. natural gas for oil). Since producers want to maximize output, given the emission constraint, resource users initially substitute towards the input which, at the margin, has the highest level of output per unit of carbon dioxide. This may be the input with most CO_2 emissions per unit of energy, in particular when this input is physically relatively scarce: it is then used in production at relatively low levels and hence diminishing returns cause its productivity to be relatively high. With an anticipated constraint, the reaction is more complex: the economy switches towards the less productive input (in terms of GDP per unit of carbon) before the constraint becomes binding and jumps towards a relatively more intensive use of the more productive input when the emission ceiling becomes binding.

A preliminary empirical investigation indicates that it is optimal to substitute away from coal towards gas and oil, but also at the same time to substitute away from low-carbon input gas towards high-carbon input oil. Hence, in order to cope with climate change, energy policies should not necessarily be directed to a fast transition to low-carbon energy sources. In addition to relative pollution content, scarcity of resources as well as their productivity differences, as shaped by substitution possibilities, should be taken into account.

The general insight from our analysis is that incorporating scarcity and intertemporal substitution in extraction into the analysis of pollution constraints may revert conclusions from the usual static models. The limited substitution between energy resources in production plays an essential role as well: demand factors are crucial in determining to which resource the economy should substitute to minimize the cost of climate change policy. These factors include the sectoral composition of the economy and the degree to which technologies of energy users is biased to a particular type of energy.

For future research it is interesting to consider the role of induced technological change in more detail, as well as that of extraction costs, uncertainty, and strategic supply reactions from monopolistic resource owners. A more detailed calibration or estimation of the model then becomes possible as well.

2.A Appendix: Proofs of Propositions

We simplify notation using variables without subscripts to denote high-carbon to low-carbon ratios: $R(t) \equiv R_H(t)/R_L(t)$, $S(t) \equiv S_H(t)/S_L(t)$ and $p(t) \equiv p_{RH}(t)/p_{RL}(t)$, and similarly $\eta \equiv \eta_H/\eta_L$, $\varepsilon \equiv \varepsilon_H/\varepsilon_L$, and $S_0 \equiv S_{H0}/S_{L0}$. For any variable x we define $x(\tau^-) \equiv \lim_{t\uparrow\tau} x(t)$ and $x(\tau^+) \equiv \lim_{t\downarrow\tau} x(t)$.

Before proving the propositions, we present and prove the following lemma, which summarizes the dynamics of relative extraction R over three relevant time periods: when the constraint is announced but not yet effective, when the constraint binds, when the constraint is not binding anymore.

Lemma 2.3. *Let $t = 0$ be the instant at which the constraint is announced, t_K be the instant at which the constraint becomes binding, and T_U the instant at which the constraint ceases to be binding. Then without further shocks*

$$R(t) = S(T_U),\ \forall\ t \in (0, t_K) \tag{2.18}$$

$$R(t) = R(T_U^-), \forall\ t \geq T_U. \tag{2.19}$$

$$\mathrm{d}R/\mathrm{d}t = f(R)\left[R^{1/\sigma} - \eta/\varepsilon\right], \forall\ t \in (t_K, T_U), \tag{2.20}$$

where f is a function of R and parameters with $f > 0$ and $\partial f/\partial \bar{Z} = 0$ for all $R > 0$,

$$\int_t^{T_U} \left(\frac{1}{1+\varepsilon R(\tau)} - \frac{1}{1+\varepsilon S(t)}\right) d\tau + \left(\frac{1}{1+\varepsilon R(T_U)} - \frac{1}{1+\varepsilon S(t)}\right)\frac{1}{\rho} = 0,$$
$$\forall\ t \in [t_K, T_U) \tag{2.21}$$

$$\mathrm{d}R(t)/\mathrm{d}t \lesseqgtr 0 \Leftrightarrow (\eta/\varepsilon)^\sigma \gtreqless R(t) \gtreqless S(t) \gtreqless R(T_U), \forall\ t \in (t_K, T_U). \tag{2.22}$$

Proof. For all $t \in [0, t_K) \cup [T_U, \infty)$ we have $p_Z = 0$ and, from (2.5), $p\,(t) = \eta\,(R\,(t))^{-1/\sigma}$. For all $t \geq T_U$, we have, from (2.11), $R\,(t) = S\,(t)$. Since p is constant over time (see (2.7)), we find $p\,(t) = \eta\,(S\,(T_U))^{-1/\sigma}\ \forall\ t$; this proves (2.18).

Prices cannot jump in absence of unexpected events due to arbitrage. Then R can only jump if output Y jumps (see (2.5)), which is ruled out by the concavity of the utility function. This proves (2.19).

To derive (2.20), substitute one of the first-order conditions (2.5) into the other to eliminate p_Z, and rewrite:

$$\frac{A^{(\sigma-1)/\sigma}\eta_L}{p_L}\left(\frac{Y}{R_L}\right)^{1/\sigma} = \frac{1 - p/\varepsilon}{1 - R^{-1/\sigma}\eta/\varepsilon}. \tag{2.23}$$

Time differentiate and substitute (2.7) and (2.2) to replace $\widehat{p_L}$ by $\widehat{Y} + \rho$:

$$(\sigma - 1)\widehat{A} - \sigma\left(\widehat{Y} + \rho\right) + \widehat{Y} - \widehat{R_L} = \frac{1}{1 - R^{1/\sigma}\varepsilon/\eta}\widehat{R}. \tag{2.24}$$

Define $\theta_L = \left(1+\eta R^{1-1/\sigma}\right)^{-1}$ and $\lambda_L = (1+\varepsilon R)^{-1}$, which are the production elasticity and share in total pollution of the low-carbon input, respectively. This implies:

$$\frac{1}{1-R^{1/\sigma}\varepsilon/\eta} = \frac{\lambda_L(1-\theta_L)}{\lambda_L-\theta_L}. \tag{2.25}$$

Time differentiating the binding emission constraint (2.4), we find $\widehat{R_H} = \lambda_L \widehat{R}$ and $\widehat{R_L} = -(1-\lambda_L)\,\widehat{R}$. Time differentiating the production function and inserting the two expressions from the emission constraint, we find:

$$\widehat{Y} = \widehat{A} + (\lambda_L - \theta_L)\,\widehat{R}. \tag{2.26}$$

Substituting (2.25) and (2.26) into (2.24) and rearranging, we find:

$$\widehat{R} = \frac{(\theta_L-\lambda_L)\,\sigma\rho}{(\theta_L-\lambda_L)^2\sigma + \theta_L(1-\theta_L)}. \tag{2.27}$$

The left-hand side of (2.23) is positive, so that $sign(\varepsilon - p) = sign\left[R-(\eta/\varepsilon)^{\sigma}\right]$. Since p and ε are constant over time, $[R-(\varepsilon/\eta)^{\sigma}]$ cannot switch sign. Since, from (2.25), $sign(\theta_L-\lambda_L) = sign\left[R-(\eta/\varepsilon)^{\sigma}\right]$, we can write (2.27) as in (2.20). This proves (2.20).

To derive (2.21), we note that the definitions of Z, R and S imply $Z\left((1+\varepsilon R)^{-1}-(1+\varepsilon S)^{-1}\right)(\varepsilon_L S_L+\varepsilon_H S_H)\,/\,(\varepsilon_L S_L \varepsilon_H S_H) = R_L/S_L - R_H/S_H$. Evaluating Z and R at time τ and S at time t, and integrating over τ from t to infinity, the right-hand side becomes zero because of full depletion (from (2.1) and (2.7)), so that, after dividing out a positive term, we may write $\int_t^{\infty} Z(\tau)\left[(1+\varepsilon R(\tau))^{-1}-(1+\varepsilon S(t))^{-1}\right]\mathrm{d}\tau = 0$. For $\tau > t_K$, $Z(\tau) = \bar{Z}$ up till T_U and $Z(\tau) = \bar{Z}e^{\rho(T_U-\tau)}$ after T_U and R is constant after T_U and continuous at T_U, according to (2.19). Then the above integral can be rewritten as in (2.21).

To proof (2.22), note that (2.21) implies that if R monotonically decreases over time, then $R(t)$ must first exceed, but eventually fall short of $S(t)$. More generally, for $\forall\ t \in (t_K, T_U)$, we have: if $\mathrm{d}R(\tau)/\mathrm{d}\tau \lesseqgtr 0$, $\forall \tau \in (t, T_U)$, then $R(t) \gtreqless S(t) \gtreqless R(T_U)$. Equation (2.20) shows that, indeed, $\mathrm{d}R/\mathrm{d}t$ cannot switch sign between t_K and T_U. Hence we have (2.22). □

2.A.1 Proof of Proposition 2.1

Prior to the unexpected constraint ($t < t_K = 0$), the economy acts like the unconstrained economy, so that, from (2.11), $R(0^-) = S(0^-) = S(0)$. Then part 1(b) follows from (2.22) with $t_K = 0$. Part 1(c) follows from (2.19) and (2.22). Part 1(a) follows from 1(c) and (2.12). From stock dynamics (2.6) we derive

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{R_L}{S_L}(S-R). \tag{2.28}$$

Combined with part 1(b) of the proposition, this proves 1(d). This completes the proof of part 1 of proposition 1. The proof of part 2 is analogous.

Finally we prove part 3 using lemma 2.2. From 1*(c)* and (2.11), we have $\left|R(0^-)-\bar{S}\right| = \left|S_0-\bar{S}\right| > \left|R(0^+)-\bar{S}\right|$ and with lemma 2.2 this proves the downward jump. The "increase over time" follows from 1*(b)*. From 1*(c)* and (2.11), we have $\left|R(0^-)-\bar{S}\right| = \left|S_0-\bar{S}\right| < \left|R(T)-\bar{S}\right|$. With lemma 2.2, this proves the higher end-level. The last part follows from (2.11).

2.A.2 Proof of Proposition 2.2

Denote by $\bar{Z}^o$ the "old" constraint that is introduced at $t=0$ and which would, in the absence of shocks, cease to bind at T^o. Denote by $\bar{Z}^n$ the "new" constraint that at time t^n unexpectedly replaces $\bar{Z}^o$, where $\bar{Z}^o > \bar{Z}^n$, and ceases to bind at T^n.

We prove part 1 by using the procedure we used for the proof of lemma 2.1 and derive T^n from (2.9), (2.10), and (2.19) in the following way:

$$\begin{aligned}
\varepsilon_H S_{H0}+\varepsilon_L S_{L0} &= [\varepsilon_H\left(S_{H0}-S_H(t^n)+S_H(t^n)-S_H(T^n)\right) \\
&\quad +\varepsilon_L\left(S_{L0}-S_L(t^n)+S_L(t^n)-S_L(T^n)\right)] \\
&\quad +\varepsilon_H S_H(T^n)+\varepsilon_L S_L(T^n) \\
&= t^n\bar{Z}^o+(T^n-t^n)\bar{Z}^n+\varepsilon_H\frac{R_H(T^n)}{\rho}+\varepsilon_L\frac{R_L(T^n)}{\rho} \\
\frac{\varepsilon_H S_{H0}+\varepsilon_L S_{L0}}{\bar{Z}^o}-\frac{1}{\rho} &= t^n+(T^n-t^n)\frac{\bar{Z}^n}{\bar{Z}^o}+\frac{\bar{Z}^n}{\bar{Z}^o}\frac{1}{\rho}-\frac{1}{\rho} \\
T^o-T^n &= \left(t^n-T^n-\frac{1}{\rho}\right)\frac{\bar{Z}^o-\bar{Z}^n}{\bar{Z}^o}
\end{aligned}$$

This explicitly solves for T^n. Since by assumption the new constraint is binding when introduced, we must have $t^n < T^n$, and hence $T^n \gtreqless T^o \iff \bar{Z}^o \lesseqgtr \bar{Z}^n$, which proves part 1.

We prove parts 2-4 for $S_{H0}/S_{L0} < \left(\eta/\varepsilon\right)^{\sigma} \equiv \bar{S}$ only; the other cases are analogous. We continue the notation of the proof of proposition 1. Since $\partial f/\partial\bar{Z}=0$ in (2.20), a decline in $\bar{Z}$ affects the equilibrium path of $R(t)$ only through an increase in T_U. Write $R^o(t)$ and $R^n(t)$ for relative extraction with the old and the new value for $\bar{Z}$ respectively. Suppose the unexpected change in the constraint would not on impact change relative extraction, i.e. $R^n(t^{n+}) = R^o(t^{n+})$. Then, from (2.20), $R^n(t) = R^o(t)\ \forall\ t \in (t^n, T^o]$, but $R^n(t) < R^o(t)\ \forall\ t \in (T^o, T^n)$ and the integral at the left-hand side of (2.21) with $R=R^n,\ t=t^n$ and $T_U=T^n$ exceeds the integral with $R=R^o, t=t^n$ and $T_U=T^o$. But this violates the equality in (2.21) for the new path. If $R^n(t^{n+}) < R^o(t^{n+})$, then the integral for the new path is positive a fortiori. Hence, we must have $R^n(t^{n+}) > R^o(t^{n+})$, which proves part 2 of the proposition.

We prove part 3 in a similar way. Suppose $R^n(T^n) = R^o(T^o)$, then $R^n(t) = R^o(t - T^n + T^o)$ for $t \in (t^n + T^n - T^o, T^n)$ and $R^n(t) > R^o(t^n)$ for $t \in (t^n, t^n + T^n - T^o)$. But then (2.21) is violated on the new path since the integral becomes negative. A fortiori (2.21) is violated with $R^n(T^n) > R^o(T^o)$. Hence we must have $R^n(T^n) < R^o(T^o)$. From (2.11) it follows that $S^n(T^n) < S^o(T^o)$, which proves part 3.

Combining the results in part 3 with (2.18), we find $R^o(T^o) = S^o(T^o) > S^n(T^n) = R^n(T^n)$. From (2.12), we then have $p^o(T^o) < p^n(T^n)$.

Part 5 directly follows from part 3 of proposition 2.1.

2.A.3 Proof of Proposition 2.3

Suppose the constraint is announced at $t = 0$, becomes binding at $t = t_K > 0$ and ceases to be binding at $t = T_A$.

Assume that $S(t_K) < \left(\eta/\varepsilon\right)^{\sigma} \equiv \bar{S}$. Then, from part 1 of proposition 1 and (2.28), we have

$$S(t_K) > S(T_A). \tag{2.29}$$

Suppose $S_0 \leq R(0^+)$. Then from (2.18), (2.19), and (2.28) the relative stock has to jump up at $t = t_K$ for (2.29) to hold, which violates continuity of stocks. So $S_0 > R(0^+) = S(T_A)$. It follows from (2.28) that $\mathrm{d}S/\mathrm{d}t > 0 \; \forall \; t \in (0, t_K)$ so that $S_0 < S(t_K)$. Since we started from the assumption $S(t_K) < \bar{S}$, we must have $S_0 < \bar{S}$. The reasoning for the cases $S(t_K) \geq \bar{S}$ are analogous. This proves parts (i) and (ii) of part 1(a), part (i) of part 1(b), and the first two results of part 2 of the proposition; parts 1(a) (iv) and 1(b)(ii) then follow from part 1 of proposition 1.

Combining (2.2) and (2.7), we find $\hat{p}_{Ri} = \rho + \hat{Y}$. Hence, either p_{Ri} and Y jump in the same direction, or both are continuous around t_K. Suppose all are continuous. Then, since a binding constraint implies $p_Z(t_K^-) = 0 < p_Z(t_K^+)$, it follows from (2.5) that both R_L and R_H jump down. However, from (2.3) this is inconsistent with constant Y. Hence we have a contradiction and p_{Ri} and Y must jump. Suppose they jump up. Then from (2.5) both R_L and R_H have to jump down percentage-wise less than Y does. But this violates the constant returns to scale property of (2.3). Hence Y must jump down. This proves the first result of part 3.

Continue with the case $S_0 < \bar{S}$ (again, the reasoning for the other cases is analogous). From part 1(a)(iv) of the proposition, $\hat{R} < 0$ for $t \in (t_K, T_A)$. From (2.18) and (2.19) we find $R(t_K^-) = R(T_A^+) = R(T_A^-)$. Combining gives $R(t_K^-) < R(t_K^+)$, which proves 1(a)(iii).

From lemma 2 and the result that R jumps closer to (or stays at) $\bar{S}$ (see 1(a)(iii), or the first result of part 3, of the proposition), we find that Z/Y jumps down (or stays constant) at implementation. This proves statement 1(c) and the last statement in part 2. Since output jumps down (first statement in part 3), Z must jump down as well. This proves the second statement of part 3.

2.A.4 Proof of Proposition 2.4

First, a binding constraint implies $\varepsilon_H S_H(t) + \varepsilon_L S_L(t) > \bar{X} - X(t)$, where the rate of change of both the left-hand side and the right-hand side equals $Z(t)$, so that if the inequality holds at $t = 0$, it holds at all $t > 0$. This allows us to drop the time indicator. Second, in section 2.6 we have shown that with the pollution constraint binding, we have $\varepsilon_H R_H + \varepsilon_L R_L = \rho\left(\bar{X} - X\right)$. Combining both results, we may write:

$$R_H = \rho S_H \iff R > S; \; R_L = \rho S_L \iff R < S. \tag{2.30}$$

Now we define $\overline{R_L} \equiv \rho\left(\bar{X} - X(0)\right) / \left(\varepsilon_L + \varepsilon_H \bar{S}\right)$ and $\overline{R_H} \equiv \overline{R_L}\bar{S}$, where $\left\{\overline{R_H}, \overline{R_L}\right\}$ are the extraction rates that give the highest possible level of output when constrained. Then the solution to (2.17) reads and implies:

1. if $S_H > \overline{R_H}/\rho$ and $S_L > \overline{R_L}/\rho$ then $R_H = \overline{R_H}$ and $R_L = \overline{R_L}$ so that $R = \bar{S}$;
2. if $S_H < \overline{R_H}/\rho$ then $R_H = \rho S_H < \overline{R_H}$ and $R_L = \overline{R_L} + \varepsilon\left(\overline{R_H} - \rho S_H\right) > \overline{R_L}$ so that, given (2.30), $S < R < \overline{R}$;
3. if $S_L < \overline{R_L}/\rho$ then $R_L = \rho S_L < \overline{R_L}$ and $R_H = \overline{R_H} + \varepsilon\left(\overline{R_L} - \rho S_L\right) > \overline{R_H}$ so that, given (2.30), $S > R > \overline{R}$.

Line 1 (line 2 and 3) proves the statements in part 2 (1) of the proposition.

2.B Appendix: Data, calibration, and regressions

In this document we describe our calibrations and empirical findings, to complement the analytical results of this chapter. We describe the construction of the data, the calibrations, and the regressions we ran to estimate technology and substitution parameters. The purpose of the calibrations and the regressions is to say something about the empirical relevance of our result that it might be optimal to substitute towards the high-carbon input, after the introduction of climate policy. We will provide evidence that it might be optimal to substitute from coal to oil and from coal to gas, but from low-carbon gas to high-carbon oil after the introduction of climate policy.

Whether there will be substitution towards the high-carbon or low-carbon input, depends on the sign in the following expression:

$$\frac{S_{H0}}{S_{L0}} \gtreqless \left(\frac{\eta_H \varepsilon_L}{\eta_L \varepsilon_H}\right)^{\sigma}. \tag{2.31}$$

When the left-hand side is smaller (larger) than the right-hand side, it is optimal to increase (decrease) relative extraction, that is it is optimal to substitute from (towards) the low-carbon input towards (from) the high-carbon input.

In the chapter, we use a CES production function:

$$Y = A\left(\eta_H R_H^{\frac{\sigma-1}{\sigma}} + \eta_L R_L^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{2.32}$$

where A is the level of total factor productivity, R_i is the amount extracted of resource $i \in \{H, L\}$, η_H and η_L are positive technology parameters and $\sigma \in (0, \infty)$ is the constant elasticity of substitution. The use of fossil fuels causes emissions of carbondioxide. The two inputs differ in their CO_2 emission intensity per unit of energy and we denote the (constant) CO_2 emission coefficients of H and L by ε_H and ε_L respectively, with $\varepsilon_H > \varepsilon_L$ so that H is the relatively dirty or high-carbon input. The total amount of emissions is denoted by Z. If the economy is subject to an emissions constraint, total emissions cannot exceed a maximally allowed amount $\bar{Z}$, according to the following constraint:

$$\varepsilon_H R_H(t) + \varepsilon_L R_L(t) = Z(t) \leq \bar{Z}. \tag{2.33}$$

As we are interested in the reaction of the economy to the constraint rather than in optimal climate policy itself, we assume that the constraint $\bar{Z}$ is exogenous.

The government allocates tradable emission permits over producers in the final goods industry, who trade them at a market price p_Z and buy resources of type i at price p_{Ri}. The price of the final good is normalized to one for every period. Firms maximize profits and the first order conditions for resource use read (from (2.32) and (2.33)):

$$A^{\frac{\sigma-1}{\sigma}}\eta_i\left(\frac{Y}{R_i}\right)^{\frac{1}{\sigma}}=p_{Ri}+\varepsilon_i p_Z. \tag{2.34}$$

This equation states that the marginal revenue from resource input i (the marginal product at the left-hand side) equals its marginal cost (the user price at the right-hand side), which consists of the price of the resource augmented with the cost of pollution in case the constraint is binding.

Taking the ratio of the first order conditions for the high- and low-carbon input, and using world variables, we find:

$$\frac{\eta_H}{\eta_L}\left(\frac{R_H^w(t)}{R_L^w(t)}\right)^{-1/\sigma}=\frac{p_{RH}^w(t)}{p_{RL}^w(t)}. \tag{2.35}$$

We assume that producers of final output, who are the consumers of the fossil fuels, take prices as given. For this, we have to rewrite (2.35) into:

$$\frac{R_H^w(t)}{R_L^w(t)}=\left(\frac{\eta_H}{\eta_L}\right)^{\sigma}\left(\frac{p_{RH}^w(t)}{p_{RL}^w(t)}\right)^{-\sigma}. \tag{2.36}$$

Rewriting this in logarithms, we get:

$$\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right)=\sigma\ln\left(\frac{\eta_H}{\eta_L}\right)-\sigma\ln\left(\frac{p_{RH}^w(t)}{p_{RL}^w(t)}\right). \tag{2.37}$$

This equation is the basis for our regressions, and together with (2.31) for our calibrations.

In the next section we describe how we constructed our data series. We then present our calibrations, using world-level data, in section 2.B.2. We present the results of our regressions using world-level demand data in section 2.B.3, and using country-level panel data in section 2.B.4. We provide and overview and conclude in section 2.B.5.

2.B.1 Data

Our data on prices and quantities for coal, oil, and gas, come from the BP Statistical Review 2006, June 2006. This is available as a Microsoft Excel file at www.bp.com/statisticalreview. In order to have all data in the same units, we constructed our data such that all prices and quantities represent million tonnes of oil equivalents (Mtoe). Unless mentioned otherwise, our conversion factors come from the same BP Statistical Review. We picked the emission coefficients for coal, oil, and gas such that they are compatible with those used by the United States Environmental Protection Agency (2006) and the German Deutsche Emissionshandelsstelle (2004), and chose $\varepsilon_{coal}/\varepsilon_{oil}=1.26$, $\varepsilon_{coal}/\varepsilon_{gas}=1.73$ and $\varepsilon_{oil}/\varepsilon_{gas}=1.37$.

Stock data

The data for coal (proven reserves, world total) are available in million tonnes, for anthracite and bituminous, and for sub-bituminous and lignite, but only for the year 2005. To convert these in million tonnes of oil equivalents, we use a conversion factor of 2/3 and 1/3 respectively, where we took the conversion factor from www.globallngonline.com. Since then the stocks are in Mtoe, we can sum the two stocks such that we have a global stock of coal.

The stock data for oil (proven reserves, world total) are available in billions of barrels, from 1980 onwards. We convert the data into million tonnes of oil using the conversion factor of the BP Statistical Review.

Data for stocks of gas (proven reserves, world total) are available in trillions cubic meters, from 1980 onwards. We use the conversion factors provided by the BP Statistical Review to convert these data in Mtoe.

Demand data

The consumption data for the three fossil fuels are all available in Mtoe, for over 70 countries and regions, and in world totals, for 1965-2005. Since the smallest unit of observation (and changes) is 0.1 Mtoe, we only include countries for which the smallest amount consumed of a particular fuel is 2.0 Mtoe or higher in our panel data regressions. That is, we remove series in which changes in demand of 0.1 Mtoe are equivalent to a percentage change of more than 5%, due to lack of scale. In addition we exclude (formerly) centrally planned countries and countries in which the oil sector has a considerable share in GDP, as we cannot assume that for all years fuel prices in these countries were determined by market forces. Finally we can only use countries that have data and fulfil the requirements for at least 2 fuels. This gives us 31 countries.

Construction of price data

In this subsection, we describe how we construct series for world prices for coal, oil, and gas. We have several prices for each of these inputs, e.g. Brent, Dubai, Nigerian Forcados and West Texas Intermediate for oil. We computed correlation coefficients for the prices for each input, to see how e.g. the 4 oil prices are correlated. For each input, the prices are highly correlated with (for the time period relevant for our analysis) correlation coefficients ranging from about 0.5 to 0.8 for coal, around and close to 0.99 for oil, and ranging from 0.91 to 0.98 for gas. To construct global fuel prices, we use quantities consumed or produced to construct weights. Data on quantities consumed and produced are available for several countries (over 70 countries in case of consumption), for 1965-2005.

Coal price For coal, the following prices are available: Northwest Europe Marker Price (1987-2005), US Central Appalachian Coal Spot Price (1990-2005), Japan Coking Coal Import CIF Price (1987-2005), Japan Steam Coal Import CIF Price (1987-2005). Prices are in dollars per tonne, hence we first have to convert prices into US dollars per Mtoe. We obtain the heat contents of coal production, in thousand Btu per short tonne, for several years and several countries from http://www.eia.doe.gov/emeu/iea/contents.html. We convert these into million Btu per metric tonne using 1 short ton = 0.9071847 metric tonne (source: http://www.eia.doe.gov/emeu/aer/pdf/pages/sec13_12.pdf). Then we convert from million Btu into Mtoe using the conversion factor of the BP Statistical Review (1 million Btu = 0.025 toe), such that we have the heat contents of coal and coke in Mtoe per metric tonne, for several years.

We assign country heat contents to prices using the following scheme:

1. Northwest Europe Marker Price - Germany, France, UK, Norway, using production-weighted average;
2. US Central Appalachian Coal Spot Price - United States;
3. Japan Coking Coal Import CIF Price - Production-weighted average of Germany, France, UK, Norway and United States;
4. Japan Steam Coal Import CIF Price - Production-weighted average of Germany, France, UK, Norway and United States.

Using this scheme, we get prices per Mtoe, for the several prices.

The next step is construct a world coal price, giving quantity weights to the prices mentioned above. We match quantities *consumed* (as coal is generally consumed within the region covered by the price's name) to the respective prices in the following manner:

1. Northwest Europe Marker Price - Germany, Norway, Finland, Sweden, Denmark, Netherlands, UK, France, Belgium, Luxemburg, Austria, Switzerland;
2. US Central Appalachian Coal Spot Price - North America (Canada, USA, Mexico);
3. Japan coking coal import cif price - 0.5*Japan;
4. Japan steam coal import cif price - 0.5*Japan;

This gives us a world coal price in US dollars per Mtoe for 1987-2005 and for 1990-2005, where the years 1987-1989 exclude the US in constructing the world price, as the price series for US Central Appalachian Coal starts in 1990.

Oil price For oil, the following prices are available: Dubai (1972-2005), Brent (1976-2005), Nigerian Forcados (1976-2005), West Texas Intermediate (1976-2005), all in US dollars per million tonnes of oil. To construct a world price, we give quantity weights to these prices, based upon quantities *produced*, as the prices can be considered prices ”at the well”, using the following matching scheme:

1. West Texas Intermediate - North America (Canada, USA, Mexico);
2. Nigerian Forcados - Nigeria;
3. Brent - UK, Norway;
4. Dubai - Total Middle East.

This gives a world price for oil in US dollars per million tonnes of oil for 1976-2005. In practice we will use shorter series as we are constrained by the availability of prices of coal and gas.

Gas price The following natural gas prices are available: European Union CIF (1984-2005), UK (Heren BNP Index, 1996-2005), USA (Henry Hub, 1989-2005), Canada (Alberta, 1990-2005). In addition we have data on LNG prices for Japan (1985-2005). All prices in dollars per million Btu. Using the conversion factors of the BP Statistical Review, we convert these prices into million dollars per Mtoe. We construct a world price using quantities *consumed*, as gas is less traded over the oceans than is oil, using the following matching scheme:

1. USA - USA;
2. Canada - Canada;
3. European Union - Austria, Belgium & Luxembourg, Denmark, Finland, France, Greece, Germany, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland;
4. UK - United Kingdom;
5. Japan - Japan.

This gives us a world price for 1984-2005, where the period 1984-1988 excludes the US due to missing price data.

2.B.2 Calibrations

In this section we use our data on stocks, consumption and prices to determine for which values of the elasticity of substitution between the high- and low-carbon fossil fuel it would be optimal to substitute from the low-carbon input to the high-carbon input. This will be the case if the inequality (2.31) turns out to have a 'smaller than' sign. If we substitute (after some rewriting) (2.36) in it and rewrite, we find

$$\frac{S_H(t)}{S_L(t)} < \frac{R_H(t)}{R_L(t)} \left(\frac{p_{RH}(t)/\varepsilon_H}{p_{RL}(t)/\varepsilon_L} \right)^{\sigma} \tag{2.38}$$

which implies that the condition for substitution towards the high-carbon input reads:

$$\frac{S_H(t)}{S_L(t)} < \left(\frac{\eta_H \varepsilon_L}{\eta_L \varepsilon_H} \right)^{\sigma} \iff \begin{cases} \sigma < \dfrac{\ln\left(\frac{S_H(t)/S_L(t)}{R_H(t)/R_L(t)}\right)}{\ln\left(\frac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right)} \text{ if } \ln\left(\dfrac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right) < 0 \\ \sigma > \dfrac{\ln\left(\frac{S_H(t)/S_L(t)}{R_H(t)/R_L(t)}\right)}{\ln\left(\frac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right)} \text{ if } \ln\left(\dfrac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right) > 0 \end{cases} \tag{2.39}$$

For every year in our data set, we can see whether this inequality holds or not. Figures 2.4, 2.5 and 2.6 present (the natural logarithm of) relative stocks, relative extraction, and relative price per unit of emissions $\left(\frac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right)$.

Coal vs. oil

Since for the stock of coal we only have data for the year 2005, we use this number for every year t in (2.39). However, since the stock of coal is nearly three times as large as the stocks of oil and gas (all in Mtoe), and we don't expect the stocks of the resources to fluctuate a lot, our results are probably not affected by this lack of data.

We first have to check what the sign is of $\ln\left(\frac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right)$. For every year t this fraction turns out to be smaller than zero. Since the fraction $\ln\left(\frac{S_H(t)/S_L(t)}{R_H(t)/R_L(t)}\right)$ is positive for every year, the ratio of these two fractions is negative. As can be seen from (2.39), this implies that there will be substitution towards the high-carbon input coal if and only if σ is smaller than a negative value. Of course, this is not possible with a CES production function, and we conclude that it will not be optimal to substitute towards coal, when compared to oil, after the introduction of a ceiling on CO_2 emissions.

Coal vs. gas

For the comparison between coal and gas, we again only have the stock of coal for the year 2005. As with coal vs. oil, the sign of $\ln\left(\frac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right)$ is negative for every year

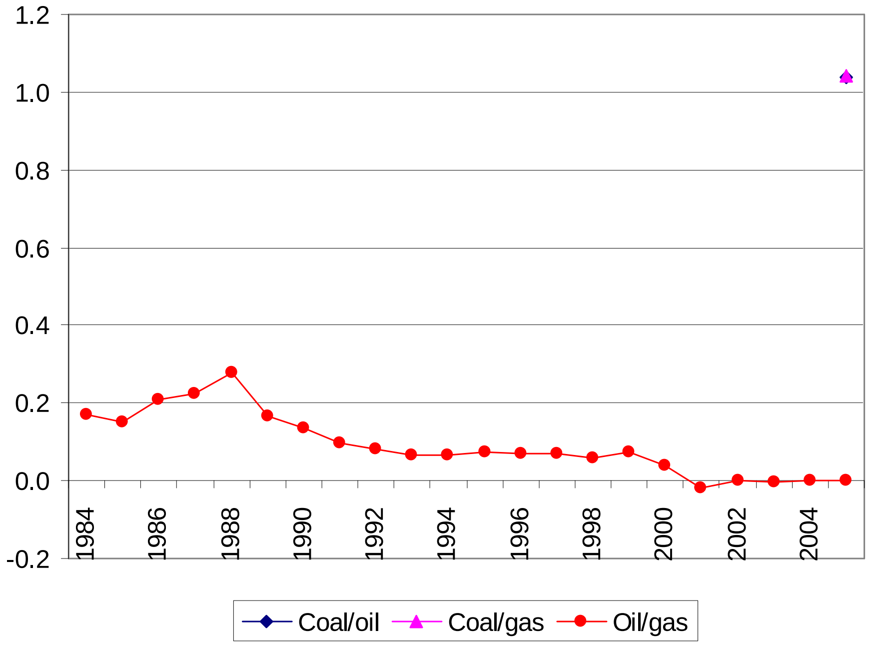

Figure 2.4: Logarithm of relative stocks

and $\ln\left(\frac{S_H(t)/S_L(t)}{R_H(t)/R_L(t)}\right)$ is positive for every year. As a consequence, we can conclude that it will not be optimal to substitute from low-carbon gas to high-carbon coal, after the introduction of climate policy.

Oil vs. gas

For oil and gas we have stock data for the period 1984-2005, for which we have price and quantity data as well.

The sign of the fraction $\ln\left(\frac{p_H(t)/\varepsilon_H}{p_L(t)/\varepsilon_L}\right)$ is not constant over time. For 11 of our 22 observations it is positive. In the 1980s and in the 2000s the sign is mostly negative, while in the 1990s it is mostly positive. The sign of the fraction $\ln\left(\frac{S_H(t)/S_L(t)}{R_H(t)/R_L(t)}\right)$ is always negative, and we conclude that for half of our observations it would be optimal to substitute from the low-carbon input gas to high-carbon oil, for any (positive) value of the elasticity of substitution. For the other half of observations this depends on the exact size of this elasticity. For these observations it will be optimal to substitute from gas to oil if the elasticity of substitution is not too large, where the critical value of σ ranges from 1.6 to 17.5 for the period 1989-2005, and from 0.6 to 4.9 for the period 1984-1988. It should be noted that the latter series is less reliable as the world gas price for these years is constructed using prices for Europe

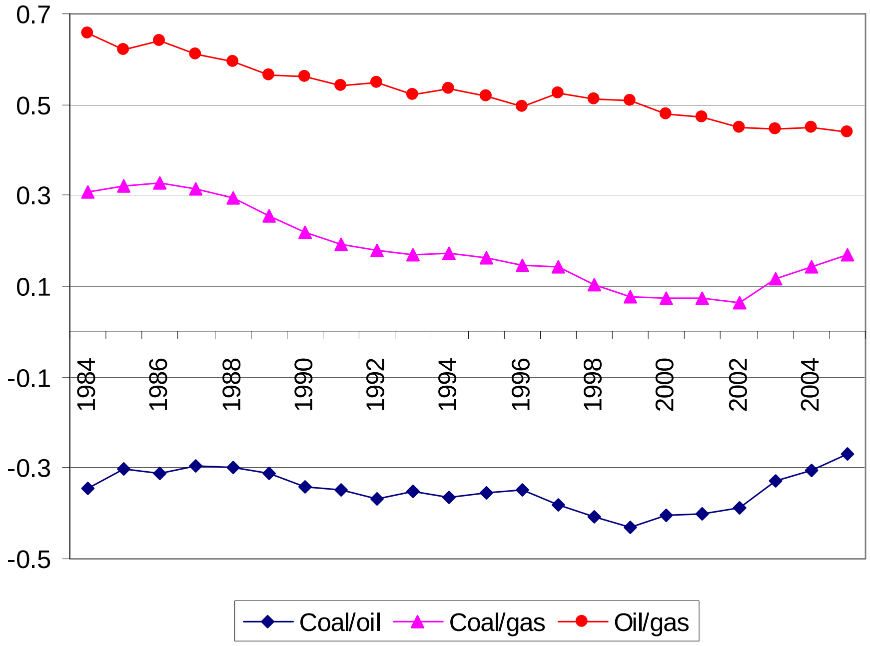

Figure 2.5: Logarithm of relative extraction

and Japan only (while for later years prices for Canada and the US are included as well).

Our calibrations suggest that, after the introduction of a ceiling on the emissions of carbon dioxide, it might be optimal to substitute from low-carbon gas to higher-carbon oil. Half of our observations give us this result, while for the other half of our observations it depends on the size of the elasticity of substitution between oil and gas. The next two sections of this document are devoted to estimating the parameters of the CES functions.

2.B.3 Regressions with world data

Although our calibrations suggest that we only need to estimate our parameters for the comparison between oil and gas, we estimate elasticities for all three comparisons (coal-oil, coal-gas, and oil-gas), and use the results for our comparison (2.31).

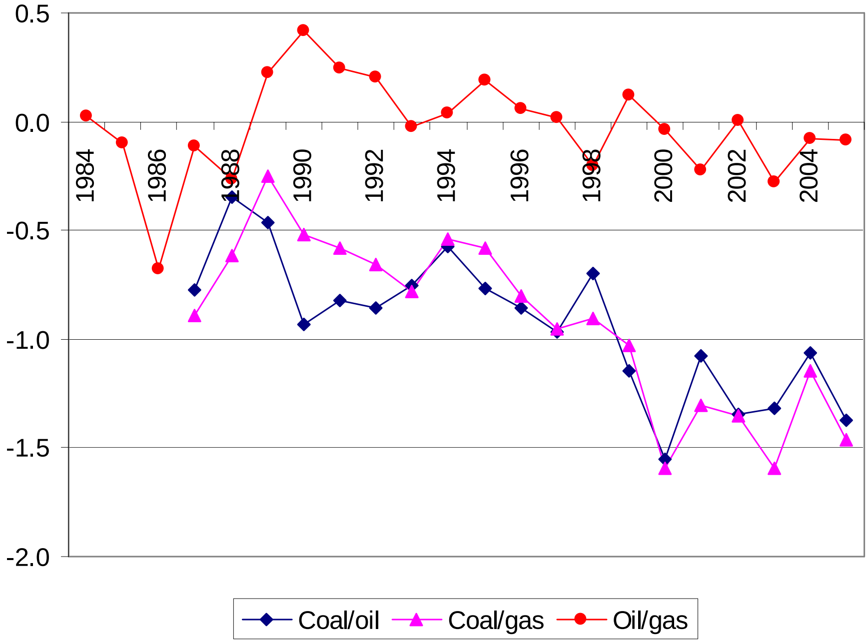

Figure 2.6: Logarithm of relative price per unit of emissions

Short-run elasticities

In this section, we take the global consumption of the fuels as the demand data, instead of the country-specific (panel) data. We present the outcomes of our comparisons (2.31), using the results from regressions using OLS. If we detected first-order autocorrelation, we also we ran regressions with the Prais-Winsten estimator.

Logs *Coal vs. oil* When we take the time series 1990-2005 for coal and oil, we find that the sign of (2.31) is positive. That is, according to our theory, the introduction of a ceiling on emissions will induce substitution towards oil, i.e. towards the low-carbon input. With the Prais-Winsten estimator we find the same results, but with both regressions we seem to have first-order autocorrelation.

When we extend the time series to the period 1987-1990, we find a negative elasticity of substitution for both estimators. Since this contradicts the properties of the CES production function, we cannot make a sensible comparison as in (2.31). Again we seem to have first-order autocorrelation, even with the Prais-Winsten estimator.

Coal vs. gas Both the time series 1990-2005 and the series 1987-2005 give us negative substitution elasticities with OLS. With Prais-Winsten we find the same for the short series, while the longer series give as outcome that the sign of (2.31) is positive (substitution towards the clean input). However, we still seem to have autocorrelation.

Oil vs. gas The time series 1989-2005 gives us a negative elasticity of substitution. If we extend the series to 1984, however, we find a positive elasticity of substitution. In this case, the comparison in (2.31) turns out to have a negative sign, both with the elasticity resulting from OLS and with the one from Prais-Winsten. According to our theory, then, the introduction of a ceiling on emissions will lead to substitution away from gas towards oil, i.e. from the low-carbon input towards the high-carbon input. Unfortunately we seem to have autocorrelation in both the OLS and the Prais-Winsten regressions.

Dlogs If we take first differences (i.e. for each variable we take its value at time t minus its value at time $t-1$), we can run our regressions in percentage changes. This should reduce the risk of having spurious regressions or unit roots, and probably autocorrelation. However, if we take first differences, we see from (2.36) that the constant term of our regressions will drop out, as $(\eta_H/\eta_L)^\sigma$ is constant over time. This implies that we have to run our regressions without an intercept. We then derive $(\eta_H/\eta_L)^\sigma$, which we need for our comparison (2.31), for the average data point in our regression $(\overline{(R_H^w/R_L^w)}, \overline{(p_{RH}^w/p_{RL}^w)})$, using (2.36) and our estimated value for σ:[21]

$$\overline{\left(\frac{R_H^w}{R_L^w}\right)} = \left(\frac{\eta_H}{\eta_L}\bigg|_{\overline{\left(\frac{R_H^w}{R_L^w}\right)},\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}}\right)^{\sigma} \overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}^{-\sigma}, \tag{2.40}$$

$$\left(\frac{\eta_H}{\eta_L}\bigg|_{\overline{\left(\frac{R_H^w}{R_L^w}\right)},\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}}\right)^{\sigma} = \overline{\left(\frac{R_H^w}{R_L^w}\right)}\,\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}^{\sigma}, \tag{2.41}$$

$$\sigma \ln\left(\frac{\eta_H}{\eta_L}\bigg|_{\overline{\left(\frac{R_H^w}{R_L^w}\right)},\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}}\right) = \ln\overline{\left(\frac{R_H^w}{R_L^w}\right)} + \sigma \ln\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}, \tag{2.42}$$

$$\frac{\eta_H}{\eta_L}\bigg|_{\overline{\left(\frac{R_H^w}{R_L^w}\right)},\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}} = \exp\left(\frac{1}{\sigma}\ln\overline{\left(\frac{R_H^w}{R_L^w}\right)} + \ln\overline{\left(\frac{p_{RH}^w}{p_{RL}^w}\right)}\right). \tag{2.43}$$

In addition, we perform the same analysis assuming that η_H/η_L is a function of time. In this case we do have an intercept in our regressions.

Constant $\frac{\eta_H}{\eta_L}$: no intercept

Coal vs. oil Although for the longer series we find a negative elasticity of substitution with the Prais-Winsten estimator, for all three other estimates we find that

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[21] Note that we have to take the averages of the ratios, not the ratios of the averages, or the averages of the logarithms of the data.

the left-hand side (LHS) of (2.31) is larger than its right-hand side (RHS). That is, our theory says that after the introduction of a ceiling on emissions, substitution will take place towards oil, the low-carbon input. All estimates seem to suffer from autocorrelation.

Coal vs. gas Except for the estimate for the longer series using OLS (in which case we find a negative elasticity), we find that the LHS of (2.31) is larger than its RHS. That is, our theory says that after the introduction of a ceiling on emissions, substitution will take place towards gas, the low-carbon input. However, all four regressions seem to suffer from autocorrelation.

Oil vs. gas Our findings for the data in percentage changes confirm what we have found when we had our data in logarithms: for the shorter time series we find a negative elasticity of substitution (and hence we cannot draw a conclusion regarding (2.31)), while for the longer series the comparison in (2.31) turns out to give a 'smaller than' sign. Our theory then suggests that climate policy will induce substitution from gas to oil at the moment of the introduction of a ceiling on emissions. Apparently, at the margin, oil gives more output per unit of emissions than gas. Again all regressions seem to suffer from autocorrelation.

Non-constant $\frac{\eta_H}{\eta_L}$: regression with intercept

If we assume that $\frac{\eta_H}{\eta_L}$ is a function of time, we do have a constant in our regressions, which is the percentage change in $\frac{\eta_H}{\eta_L}$, multiplied by σ. However, since we do not know the initial $\frac{\eta_H}{\eta_L}$, we cannot derive $\frac{\eta_H(t)}{\eta_L(t)}$. We use this regression as a 'robustness check' for the regressions without an intercept, and derive $\frac{\eta_H}{\eta_L}\Big|_{\overline{\left(\frac{R^w_H}{R^w_L}\right)},\overline{\left(\frac{p^w_{RH}}{p^w_{RL}}\right)}}$ in the same way as above. The use of an intercept in our regressions might give us a different value for σ, and hence a different value for $\frac{\eta_H}{\eta_L}\Big|_{\overline{\left(\frac{R^w_H}{R^w_L}\right)},\overline{\left(\frac{p^w_{RH}}{p^w_{RL}}\right)}}$ and possibly a different result for our comparison (2.31), compared to the regressions without intercept.

Coal vs. oil The short series gives us a positive elasticity that does not suffer from autocorrelation, for the OLS estimator. In addition, it gives us a 'greater than' sign in (2.31). With the longer series we find a negative elasticity. The Prais-Winsten estimator gives us twice a 'greater than' sign, but for both series we reject the null of no autocorrelation.

Coal vs. gas The regressions with an intercept confirm what we found with the regressions without an intercept: a negative elasticity for the short series with OLS, and a 'greater than' sign in (2.31) for the other estimates. All regressions seem to suffer from autocorrelation.

Oil vs. gas For OLS, the regressions with the short series gives a negative elasticity of substitution. The other estimates give us 'less than' sign in (2.31). Again all 4 regressions seem to suffer from autocorrelation.

Long-run elasticities

In the previous section we constructed our comparison (2.31) using the results from regressions for short-run elasticities. In this section, we present the results from regressions based upon long-run elasticities. For this, we include a lagged-dependent variable in our regressions. For the case of exogenous prices, we then write:

$$\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right) = \sigma_{SR}\ln\left(\frac{\eta_H}{\eta_L}\right) - \sigma_{SR}\ln\left(\frac{p_{RH}^w(t)}{p_{RL}^w(t)}\right) + \gamma\ln\left(\frac{R_H^w(t-1)}{R_L^w(t-1)}\right). \tag{2.44}$$

When we estimate this equation, we do not only find estimates for η_H/η_L and for the short-run elasticity σ_{SR}, we also find the coefficient for the lagged dependent variable γ.

We can rewrite this equation to include expectations:

$$E\left[\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right)\right] = \sigma_{SR}\ln\left(\frac{\eta_H}{\eta_L}\right) - \sigma_{SR}E\left[\ln\left(\frac{p_{RH}^w(t)}{p_{RL}^w(t)}\right)\right] + \gamma\ln\left(\frac{R_H^w(t-1)}{R_L^w(t-1)}\right). \tag{2.45}$$

Assuming stationarity, we have $E\left[\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right)\right] = \ln\left(\frac{R_H^w(t-1)}{R_L^w(t-1)}\right)$. Substituting this into the equation with expectations, we find after some rewriting:

$$\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right) = \frac{\sigma_{SR}}{1-\gamma}\ln\left(\frac{\eta_H}{\eta_L}\right) - \frac{\sigma_{SR}}{1-\gamma}\ln\left(\frac{p_{RH}^w(t)}{p_{RL}^w(t)}\right). \tag{2.46}$$

This shows that we can derive the long-run elasticity of substitution as $\sigma_{LR} = \frac{\sigma_{SR}}{1-\gamma}$, where we obtain estimates for σ_{SR} and γ from (2.44).

When we write out the variance of $\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right)$, we find after some rewriting and assuming stationarity:

$$Var\left(\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right)\right) = \frac{(-\sigma_{SR})^2}{1-\gamma^2}Var\left(\ln\left(\frac{p_{RH}^w(t)}{p_{RL}^w(t)}\right)\right) + \frac{s^2}{1-\gamma^2}, \tag{2.47}$$

where s^2 is the variance of the error term. Since a variance cannot be negative, we must have $|\gamma| < 1$ for a positive and finite variance for $\ln\left(\frac{R_H^w(t)}{R_L^w(t)}\right)$.

Logs We only use the OLS estimator, as Prais-Winsten cannot be used in the presence of a lagged dependent variable.

The question is whether we can have $\gamma < 0$. The chapter suggests that when there is no climate policy, the ratio of the two extraction rates is constant over time, which imposes no further restrictions on γ (see (2.46)). In the presence of climate policy, however, the ratio of the extraction rates monotonically increases or decreases, or is constant, and the same holds for the relative user's price (i.e. the price including the permit price). From (2.44) then follows that we must have $\gamma > 0$, since otherwise we would have oscillations in the relative extraction rate, which contradicts what we find in the main text. We conclude, therefore, that we have to restrict our analysis to regressions that give an estimated $0 < \gamma < 1$.

Coal vs. oil For the both time series, we find that the estimate for the coefficient for the lagged dependent variable, γ, is larger than 1. This contradicts stationarity, and hence we cannot derive an estimate for the long-run elasticity of substitution.

Coal vs. gas For the short time series, we find $\gamma > 1$. For the longer time series we find a 'larger than' sign for (2.31). Durbin's test rejects the null of no serial correlation at the 5% significance level.

Oil vs. gas For the 1989-2005 time series, we find a negative elasticity of substitution. However, when we extend our time series to 1985, we find both a positive short-run elasticity of substitution and $0 < \gamma < 1$. When we plug the estimates for our parameters into (2.31), we find a 'smaller than' sign. This result is in line with what we have found so far for the comparison between oil and gas: whenever we find parameter-values that do not contradict the properties of the CES production function (and in this case do not contradict stationarity), we find that it might be optimal to substitute from gas towards oil at the instant of the imposition of a ceiling on emissions. Durbin's test rejects the null at the 5% level, so we have an indication of autocorrelation.

Dlogs If we want to estimate long-run elasticities using data in percentage changes (first differences of logarithms), we have to combine the steps of section 2.B.3, and the steps described above. As when we estimated short-run elasticities with data in first differences of logarithms, we first look at regressions without an intercept, and then look at the results that come from regressions that do include a constant term.

Again we can only include results for which $|\gamma| < 1$ for a positive and finite variance. However, we now include negative γs, as this now implies an oscillating growth rate of relative extraction, instead of an oscillating level.

Constant $\frac{\eta_H}{\eta_L}$: no intercept

Coal vs. oil For both the 1991-2005 and 1989-2005 time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities, when we compare coal and oil. The regression with the longer series seems to suffer from autocorrelation.

Coal vs. gas For both time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities, when we compare coal and oil. We cannot reject the null of no autocorrelation for both series.

Oil vs. gas The 1991-2005 series gives a negative long-run elasticity of substitution, while the 1986-2005 series gives a ’smaller than’ sign for our comparison (2.31), which is what we found for some of the short-run elasticities as well. We cannot reject the null of no autocorrelation for both series.

Non-constant $\frac{\eta_H}{\eta_L}$: regression with intercept

Coal vs. oil As in the case of no intercept, we find a ’greater than’ sign for (2.31) for both time series. We cannot reject the null of no autocorrelation for both series.

Coal vs. gas As in the case of no intercept, we find a ’greater than’ sign for (2.31) for both time series. We cannot reject the null of no autocorrelation for both series.

Oil vs. gas As in the case of no intercept, the 1991-2005 series gives a negative short-run elasticity of substitution, while the 1986-2005 series gives us the result that climate policy induces the economy to increase relative extraction, i.e. use relatively more of the high-carbon input oil compared to the situation before climate policy. We cannot reject the null of no autocorrelation for both series.

2.B.4 Regressions with panel data

In this section, we use country-level data for the demand for fuels. However, we still use world prices. With panel data, we can run pooled regressions, and we can exploit the two dimensions of the data by estimating fixed effects, using the within-group estimator.[22]

Short-run elasticities

Logs When we use the data in logarithms, as in (2.37), the fixed-effects models give negative elasticities for all estimations In addition, we cannot reject the null hypothesis that all fixed effects have the same value, in which case we could use OLS or GLS. When testing for autocorrelation, the null hypothesis of no serial correlation is rejected in all cases, and we conclude that the models with panel data in logarithms suffers from specification errors.

Dlogs When we use fixed effects, we can by construction only estimate models with an intercept. We can never reject the null hypothesis that all fixed effects are the same (in which case we could use OLS or GLS with an intercept), and given that in each regression several of the fixed effects differ significantly from zero, we

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[22] Note that we cannot use the between-group estimator, as the price series are identical for each country.

can neither reject the null of no intercept. In addition, we can never reject the null hypothesis of no autocorrelation, so the model seems to be well-specified.

Coal vs. oil For the 1989-2005 time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities, when we compare coal and oil. The short series gives us a negative elasticity of substitution.

Coal vs. gas For both time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities, when we compare coal and oil.

Oil vs. gas Both series give a negative elasticity of substitution.

Long-run elasticities

Including a lagged dependent variable in a panel data implies that we estimate a dynamic panel data model. For this we use the Arellano-Bond estimator, where the first difference of the exogenous variable is used as an instrument for the exogenous variable (the logarithm of the relative price, or the first difference of the logarithm of the relative price). An important assumption here is that there is no second-order autocorrelation in the regression in differences, and this assumption holds for all our regressions.

Logs *Coal vs. oil* For both the 1991-2005 and 1989-2005 time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities and above for the long-run elasticities, when we compare coal and oil. We cannot reject the null of no second-order serial correlation.

Coal vs. gas For both time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities and above for the long-run elasticities, when we compare coal and oil. We cannot reject the null of no second-order serial correlation.

Oil vs. gas Both series give a negative elasticity of substitution. We cannot reject the null of no second-order serial correlation.

Dlogs Contrary to the case where we estimated short-run elasticities, we can estimate the long-run elasticities both for the models with and without intercepts, since we now use the Arellano-Bond estimator instead of fixed effects.

Constant $\frac{\eta_H}{\eta_L}$: no intercept

Coal vs. oil For both the 1991-2005 and 1989-2005 time series, we find a negative elasticity of substitution. We cannot reject the null of no second-order serial correlation.

Coal vs. gas For both time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities and above for the long-run elasticities, when we compare coal and oil. We cannot reject the null of no second-order serial correlation.

Oil vs. gas Both series give a negative elasticity of substitution. We cannot reject the null of no second-order serial correlation.

Non-constant $\frac{\eta_H}{\eta_L}$: regression with intercept

Coal vs. oil For both the 1991-2005 and 1989-2005 time series, we find a negative elasticity of substitution.

Coal vs. gas For both time series, we find that the sign in (2.31) is a 'greater than' sign. This is in line with what we have found so far for the short-run elasticities and above for the long-run elasticities, when we compare coal and oil. The model seems to contain no second-order serial correlation.

Oil vs. gas The short series gives a negative elasticity of substitution. The longer series gives a 'smaller than' sign, which is what we have found so far for this case (if we found a non-negative elasticity). Both models seems to contain no second-order serial correlation.

2.B.5 Conclusion

In this document we have confronted our analytical result that, under certain conditions, it is optimal to substitute from a low-carbon input to a high-carbon input, after the introduction of a ceiling on the emissions of carbon dioxide.

We first used our data to calibrate (2.39). From this calibration we concluded that it will never be optimal to substitute from low-carbon oil to high-carbon coal, or from low-carbon gas to high-carbon coal. For the comparison between oil and gas, however, our calibration gave mixed results. For some years in our data it was optimal to substitute from the low-carbon input to the high-carbon input. For other years this depended on the exact size of the elasticity of substitution.

Our regressions confirm what we found for coal-oil and for coal-gas in our calibration: it is never optimal to substitute towards coal after the introduction of climate policy. For the comparison between oil and gas we found weak evidence that it is optimal to substitute from low-carbon gas to high-carbon oil: although our regressions show several problems (negative elasticities, autocorrelation and/or insignificant results for many regressions), those regressions without autocorrelation and with positive elasticities all suggest that it is optimal to substitute from low-carbon gas to high-carbon oil.

Tables 2.1 and 2.2 give an overview of comparisons using (2.31), based upon our regressions in sections 2.B.3 and 2.B.4. Our results are consistent over short- and long-run elasticities, over the type of data used (world-level demand data, country-level demand data) and over whether we use data in logarithms or in percentage changes. Whenever we have a result, we see that the sign for the comparison between coal and oil is 'greater than', for the comparison between coal and gas 'greater than', and for the comparison between oil and gas 'smaller than'. This suggests that after the introduction of a ceiling on emissions, substitution from coal to the cleaner inputs oil and gas will take place (thereby confirming the results of the calibrations), while at the same time there will be substitution from gas towards the dirtier input oil.

Of course the results from our regressions are very preliminary. We use quite short data series for the world-level demand data, and the construction of some of the price series was quite problematic due to missing data (especially for that part of the 'longer series' that was missing in the 'shorter series'). In addition there seems to be autocorrelation in virtually all our regressions for the short-run elasticity using world data, and for the short-run elasticities with panel data in logarithms. However, about half of our regressions for long-run elasticities, both using panel and for world-level data, give a positive substitution elasticity and do not suffer from serial correlation, and the same holds for the estimates for short-run elasticities using panel data in percentage changes. All these results show the same pattern in substitution regarding our analytical results: the introduction of climate policy induces substitution from coal to oil and from coal to gas (i.e. from the high-carbon input to the low-carbon input), but from gas to oil (i.e. from the low-carbon input to the high-carbon input). The former result followed from our calibration. The latter result gives us a decisive answer for half of our observations for the oil-gas comparison: for those years where the calibration could not give a decisive answer, our regressions indicate that it would be optimal to substitute from low-carbon gas to high-carbon oil.

Our analytical result that it might be optimal to substitute from a low-carbon input towards a high-carbon input after the introduction of a ceiling on carbon dioxide emissions is hence not just an abstract theoretical possibility. Calibration using real-world data suggest that this might indeed hold for the comparison between oil and gas, and this is confirmed by our empirical results: the elasticity of substitution between oil and gas is so low that with climate policy, given our price, consumption and stock data, it is optimal to substitute from low-carbon gas to higher-carbon oil.

Table 2.1: **Overview of results of comparisons: world data**[a]

	Short-run elasticities			Long-run elasticities		
	Coal-oil	Coal-gas	Oil-gas	Coal-oil	Coal-gas	Oil-gas
OLS						
Logarithms						
Short series	>	n.a.	n.a.	n.a.	n.a.	n.a.
Longer series	n.a.	n.a.	<	n.a.	>	<
Percentage changes, without intercept						
Short series	>	n.a.	n.a.	>	>	n.a.
Longer series	n.a.	>	<	>	>	<
Percentage changes, with intercept						
Short series	>	n.a.	n.a.	>	>	n.a.
Longer series	n.a.	>	<	>	>	<
Prais-Winsten (short-run only)						
Logarithms						
Short series	>	n.a.	n.a.			
Longer series	n.a.	>	<			
Percentage changes, without intercept						
Short series	>	>	n.a.			
Longer series	>	>	<			
Percentage changes, with intercept						
Short series	>	>	<			
Longer series	>	>	<			

[a] 'n.a.' means that no result is available, due to $\sigma < 0$ or $\gamma < 0$ or $\gamma > 1$ or $\delta < 0$ or $\delta > 1$.

Table 2.2: **Overview of results of comparisons: panel data**[a]

	Short-run elasticities			Long-run elasticities		
	Coal-oil	Coal-gas	Oil-gas	Coal-oil	Coal-gas	Oil-gas
Fixed effects				**Arellano-Bond**		
Logarithms				*Logarithms*		
Short series	n.a.	n.a.	n.a.	>	>	n.a.
Longer series	n.a.	n.a.	n.a.	>	>	n.a.
Percentage changes, without intercept						
Short series				n.a.	>	n.a.
Longer series				n.a.	>	n.a.
Percentage changes, with intercept						
Short series	n.a.	>	n.a.	n.a.	>	n.a.
Longer series	>	>	n.a.	n.a.	>	<

[a] 'n.a.' means that no result is available, due to $\sigma < 0$ or $\gamma < 0$ or $\gamma > 1$ or $\delta < 0$ or $\delta > 1$.

2.B.6 Regression results

World data

Tables 2.3 and 2.4 present the estimated substitution elasticities, plus indications of significance and autocorrelation. Only 1 estimate for short-run elasticities does not suffer from autocorrelation and have the right sign. For the long-run elasticities we have better results: 9 out of 18 elasticities are positive and come from regressions without serial correlation.

Table 2.5 shows the values for η_H/η_L we use for our comparisons using world data. The results seem generally not realistic, due to extremely large or extremely small values. This is due to the sensitivity of the expression for η_H/η_L for the size of the intercept in the regression and the size of the elasticity of substitution, as $\eta_H/\eta_L = e^{intercept/\sigma}$. For the regressions in first differences of logarithms, we had to derive our η_H/η_L using the 'average observation', see equation (2.43). Here we also use powers and logarithms to derive η_H/η_L, and hence our results are sensitive to, for example, the mean relative price to be larger or smaller than 1.

Table 2.3: **Overview of elasticities: world data, short-run elasticities**

	Coal-oil	Coal-gas	Oil-gas
OLS with robust std. errors			
Logarithms			
Short series	0.0083a	-0.0887a***	-0.1696***
Longer series	-0.0335a	-0.1174a***	0.0267a
Percentage changes, without intercept			
Short series	0.0127a	-0.0038a	-0.0236a
Longer series	-0.0008a	0.0054a	0.0154a
Percentage changes, with intercept			
Short series	0.0108	-0.00042a	-0.0192a
Longer series	-0.0014a	0.0093a	0.0162a
Prais-Winsten			
Logarithms			
Short series	0.0144a	-0.0097	-0.0290a
Longer series	-0.0002a	0.0013a	0.0148a
Percentage changes, without intercept			
Short series	0.0138a	0.0121a	-0.0219a
Longer series	0.0029a	0.0131a	0.0161a
Percentage changes, with intercept			
Short series	0.0132a	0.0129a	0.0008a
Longer series	0.0027a	0.0134a	0.0208a**

a Null hypothesis ’no serial correlation’ rejected at 5% level.

*/**/*** denotes coefficient significant at 10/5/1% level.

Table 2.4: **Overview of elasticities: world data, long-run elasticities**

	Coal-oil	Coal-gas	Oil-gas
OLS with robust std. errors			
Logarithms			
Short series	$\gamma > 1$	$\gamma > 1$	-0.1455**
Longer series	$\gamma > 1$	3.1820a	0.1881a
Percentage changes, without intercept			
Short series	0.0567	0.0757	-0.0206
Longer series	0.0271a	0.1479	0.0159
Percentage changes, with intercept			
Short series	0.0518	0.0755	-0.0105
Longer series	0.0261	0.1322	0.0072

a Null hypothesis 'no serial correlation' rejected at 5% level

$^{*}/^{**}/^{***}$ denotes coefficient significant at 10/5/1% level.

Panel data

Tables 2.6 and 2.7 present the estimates of the substitution elasticities from panel data. Only 3 out of 12 estimates have the correct sign and do not suffer from serial correlation. Again, for the long-run elasticities the results are better, with 9 out of 18 elasticities having the right sign and no autocorrelation, of which 3 differ significantly from zero.

As with the world-level demand data, the values for η_H/η_L are generally extremely high or extremely low.

Table 2.5: **Overview of η_H/η_L: world data**[a]

	Short-run elasticities			Long-run elasticities		
	Coal-oil	Coal-gas	Oil-gas	Coal-oil	Coal-gas	Oil-gas
OLS						
Logarithms						
Short series	4.0e-20	n.a.	n.a.	n.a.	n.a.	n.a.
Longer series	n.a.	n.a.	5.2e+8	n.a.	0.58	12.4
Percentage changes, without intercept						
Short series	2.1e-13	n.a.	n.a.	1.2e-6	105.0	n.a.
Longer series	n.a.	9.9e+14	1.6e+15	7.3e-12	213.1	5.2e+13
Percentage changes, with intercept						
Short series	1.1e-15	n.a.	n.a.	4.6e-7	103.1	n.a.
Longer series	n.a.	3.6e+8	3.0e+14	3.3e-12	221.5	2.5e+22
Prais-Winsten (short-run only)						
Logarithms						
Short series	5.2e-11	n.a.	n.a.			
Longer series	n.a.	9.5e+67	8.9e+15			
Percentage changes, without intercept						
Short series	1.9e-12	4.2e+4	n.a.			
Longer series	1.8e-53	1.1e+6	3.2e+14			
Percentage changes, with intercept						
Short series	5.0e-13	2.1e+4	2.5e+274			
Longer series	2.0e-57	8.1e+5	1.9e+11			

[a] 'n.a.' means that no result is available, due to $\sigma < 0$ or $\gamma < 0$ or $\gamma > 1$ or $\delta < 0$ or $\delta > 1$.

Table 2.6: **Overview of elasticities: panel data, short-run elasticities**[a]

	Coal-oil	Coal-gas	Oil-gas
Fixed effects			
Logarithms			
Short series	-0.0664a**	-0.4389a***	-0.6316a***
Longer series	-0.1422a***	-0.5007a***	-0.0930a*
Percentage changes, with intercept			
Short series	-0.0020	0.0197	-0.0100
Longer series	0.0056	0.0080	-0.0051

a Null hypothesis ’no serial correlation’ rejected at 5% level

*/**/*** denotes coefficient significant at 10/5/1% level.

Table 2.7: **Overview of elasticities: panel data, long-run elasticities**

	Coal-oil	Coal-gas	Oil-gas
Arellano-Bond estimator			
Logarithms			
Short series	0.1836	0.5067*	-0.2015
Longer series	0.2637**	0.5923*	-0.4402
Percentage changes, without intercept			
Short series	-0.0038	0.0273	-0.0209
Longer series	-0.0009	0.0203	-0.0018
Percentage changes, with intercept			
Short series	-0.0029	0.0335	-0.0207
Longer series	-0.0023	0.0061	0.0020

a Null hypothesis ’no serial correlation’ rejected at 5% level.

*/**/*** denotes coefficient significant at 10/5/1% level.

Table 2.8: **Overview of η_H/η_L: panel data**[a]

	Short-run elasticities			Long-run elasticities		
	Coal-oil	Coal-gas	Oil-gas	Coal-oil	Coal-gas	Oil-gas
Fixed effects				**Arellano-Bond**		
Logarithms						
Short series	n.a.	n.a.	n.a.	0.95	0.89	n.a.
Longer series	n.a.	n.a.	n.a.	0.94	0.92	n.a.
Percentage changes, without intercept						
Short series				n.a.	5.9e+8	n.a.
Longer series				n.a.	4.3e+17	n.a.
Percentage changes, with intercept						
Short series	n.a.	2.2e+11	n.a.	n.a.	8.9e+6	n.a.
Longer series	5.1e-26	3.3e+42	n.a.	n.a.	2.3e+58	8.5e+260

[a] 'n.a.' means that no result is available, due to $\sigma < 0$ or $\gamma < 0$ or $\gamma > 1$ or $\delta < 0$ or $\delta > 1$.

CHAPTER 3

Optimal paths of extraction and emissions when climate policy is announced in advance[23]

Climate policy changes the relative price of fossil fuels, e.g. through a carbon tax or through a cap and trade system, and induces firms in most sectors of the economy to substitute away from fuels and intermediate inputs with high carbon content. These behavioural adjustments are restricted by the stocks of machines and equipment currently installed, as well as by available alternative technologies. An unexpected restriction of the production possibilities frontier might lead to high costs for firms, for example through a sudden drop in the value of the capital stock. Announcement of climate policy, however, can reduce the overall burden of the policy by giving agents time to prepare.

Although the Kyoto Protocol was agreed upon in December 1997, it only entered force in February 2005, due to the underlying requirements.[24] Had the Protocol been ratified by a sufficient number of countries immediately, then still the Protocol stated that it would only enter into force 90 days after the requirements had been met. In any case, agents were well before the start on January 1, 2008, of the Protocol's first 'commitment period' informed that a policy on greenhouse gas emissions was likely to enter force. Such anticipated policy still leaves agents free to emit in the period between announcement and implementation. This raises the question how carbon dioxide emissions respond to the announcement of future climate policy.

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[23] This chapter is based upon joint work with Corrado Di Maria and Sjak Smulders.

[24] At least 55 Parties, with Annex I countries representing at least 55% of 1990 Annex I carbon dioxide emissions, needed to ratify the Protocol before it could enter into force.

In this chapter we study how emissions, in the period between announcement and implementation of a ceiling on carbon dioxide emissions, are affected by the announcement. We use a Hotelling (1931)-style model in which utility is derived from consuming electricity, which is produced using a non-renewable resource. We abstract from physical capital and inter-fuel substitution (see chapter 2), and focus on the optimal extraction path of the resource and the associated optimal emission path, following the announcement. When the economy faces a future constraint on carbon dioxide emissions, consumers face a trade-off between consuming more in the short-run while knowing that emissions will have to be reduced at a known point in time on the one hand, and avoiding a jump in consumption at the instant of implementation through consumption smoothing, at the other.

We show that optimal resource extraction induces an *increase* in emissions at the instant of announcement. The announcement of a restriction on future emissions causes an abundance effect: whereas it is optimal to extract the entire resource stock over time, it is known that at some future date less can be extracted than agents would like to. The difference between this restriction level and the optimal path has then to be extracted either after the instant at which optimal unrestricted emissions equal the level of the ceiling, or between the instants of announcement and implementation. The solution is to do a bit of both: postponing all extraction implies high levels of utility in the future, which are then severely discounted, while extracting all of the ’extra’ resource before the constraint becomes binding brings along low levels of marginal utility in comparison with a more gradual extraction path. As a consequence, resource extraction and emissions increase at the instant of the policy’s announcement.

Furthermore we show that it is optimal to have a downward jump in extraction and utility at the instant of implementation. Finally, we show that the upward jump in emissions at announcement is larger when the instant at which the policy comes into force is closer.

Few papers study the effects of announced climate policy, and none has studied the effect of announcement on emissions. In chapter 2 of this thesis (and in Smulders and van der Werf, 2008) we studied climate policy in a 2-resource model and focused on relative extraction. We showed that when the resources are imperfect substitutes, announcement of a ceiling on the flow of emissions induces substitution towards the high- or the low-carbon input, depending on the marginal productivity of carbon for and the relative scarcity of the two fuels. However, as we focussed on the relative extraction of the two fuels, we did not study the effect of announced policy on emissions of carbon dioxide. Kennedy (2002) and Parry and Toman (2002) focus on domestic climate policies in the period between announcement and implementation of international climate policy, and argue that policies aimed at emission reductions in this period may be costly and inefficient. Kennedy

(2002) shows that, given a future ceiling on emissions, additional policy aimed at emission reductions before the future policy becomes enforced leads to too low investment in research and development and too much early capital investment, as the latter lead to immediate emission reductions whereas the former only lead to future emission reductions. Parry and Toman (2002) show that emission reductions before the commitment phase are efficient when banking of credits is allowed. This was not the case for the Kyoto Protocol. In this chapter we do not look at additional policies aimed emission reduction in the pre-commitment phase and only focus on the effects of announcement of the climate policy on emissions.

The remainder of this chapter develops as follows. In section 3.1 we introduce the basic model, which is used throughout this chapter. We then study extraction in an economy that never faces a binding emission constraint in section 3.2. We introduce an initially binding constraint in section 3.3, and study an announced constraint in section 3.4. Our main results are summarized in Proposition 3.1. In section 3.5 we study comparative dynamics with respect to some parameters representing preferences . We conclude in section 3.6.

3.1 The model

Consumers maximize intertemporal utility, while instantaneous utility U (which is a $\mathscr{C}^2$ function such that $U' > 0$ and $U'' < 0$) comes from the use of a nonrenewable resource. One unit of resource use causes ε units of emissions of carbon dioxide Z. At some point in time $T \geq 0$, the economy faces a ceiling on the amount of emissions, denoted by $\bar{Z}$.

We formulate the model as follows:

$$\max_{\{R(t)\}_0^\infty} \int_0^\infty U(R(t))\mathrm{e}^{-\rho t}\mathrm{d}t; \tag{3.1}$$

$$\dot{S}(t) = -R(t),\ R(t) \geq 0,\ S(0) = S_0; \tag{3.2}$$

$$Z(t) \equiv \varepsilon R(t) \leq \bar{Z}\ \forall t \geq T; \tag{3.3}$$

$R(t)$ denotes extraction of the nonrenewable at time t, and ρ is the rate of time preference. Equation (3.2) shows that the stock S of the nonrenewable declines with extraction (we define, for any variable x, $\dot{x} \equiv \mathrm{d}x/\mathrm{d}t$). The initial endowment of the resource, S_0, is finite and given. Climate policy is described in (3.3): emissions Z arise from resource use, but starting at time T, they cannot exceed $\bar{Z}$ (i.e., we put a constraint on the control variable R).

3.2 An economy without (the prospect of) climate policy

Let us first look at the case where the constraint will never be binding ($\bar{Z} \to \infty$). To find the optimal path of resource use, we apply a variational argument.

Along the optimal trajectory, a shift over an infinitesimal interval of time of an infinitesimal amount of resources should not affect the value of the functional (3.1). If we decrease extraction at time t by ΔR for a period of length Δt, and instead extract and consume this amount during an interval of length Δt starting at time $s > t$, this should not affect total welfare. That is,

$$U'(R(t))e^{-\rho t}\Delta R \Delta t + U'(R(s))e^{-\rho s}(-\Delta R)\Delta t = 0. \tag{3.4}$$

Dividing both sides by $\Delta R \Delta t$, and rearranging, we find:

$$\frac{U'(R(t))}{U'(R(s))} = e^{-\rho(s-t)}, \tag{3.5}$$

that is, discounted marginal utility should be equal at each point in time, or equivalently, along the optimal trajectory the marginal rate of substitution equals the marginal rate of transformation. When s approaches t, we find that the RHS of (3.5) approaches 1. Hence, $R(s) = R(t)$, and extraction must be continuous.

Secondly, we can substitute (3.2) in (3.1) and derive the Euler equation. First, define

$$\eta(R(t)) \equiv -U''(R(t))R(t)/U'(R(t)) > 0 \,\forall t \tag{3.6}$$

and $\hat{x} \equiv \dot{x}/x$ for any variable x. With this, we find the Euler equation

$$\hat{R}(t) = -\frac{\rho}{\eta(R(t))}. \tag{3.7}$$

From this and (3.3) we find

$$\hat{Z}(t) = -\frac{\rho}{\eta(R(t))}. \tag{3.8}$$

For the rest of this chapter, denote extraction of an economy that is unconstrained at all points in time by $\widetilde{R}(t)$. We summarize our results in the following Lemma:

Lemma 3.1. *Let* $\{\widetilde{Z}(t) = \varepsilon \widetilde{R}(t)\}_0^\infty$ *denote the path of emissions of the economy that is unconstrained at all points in time, as described in* (3.1)-(3.2). *Then*

1. $\hat{\widetilde{Z}}(t) = \hat{\widetilde{R}}(t) = -\frac{\rho}{\eta(R(t))}, \forall t;$
2. $\frac{U'(\widetilde{R}(t))}{U'(\widetilde{R}(s))} = e^{-\rho(s-t)}, \forall t, s;$
3. $\widetilde{Z}(t)$ *is continuous.*

Proof. Proofs of parts 1 and 2 in text; part 3 follows from part 1. □

3.3 An economy with an initially binding constraint

When an economy is initially constrained in its emissions of carbon dioxide (that is, $T = 0$) such that $Z(t) \leq \bar{Z}\,\forall\, t$, and $\widetilde{R}(0) > \bar{Z}/\varepsilon$, it is effectively constrained in its resource extraction for the period during which the emissions constraint is binding. The extraction path of the economy after the constraint ceases to be binding is described by the following Lemma:

Lemma 3.2. *Let* $\{\breve{Z}(t) = \varepsilon\breve{R}(t)\}_0^\infty$ *denote the path of emissions of the economy facing an initially binding emissions constraint* $\breve{Z}(t) \leq \bar{Z} < \varepsilon\widetilde{R}(0)\ \forall\ t$*, as described in* (3.1)-(3.3) *with* $T = 0$*. Define* $T_H \equiv \{t|\breve{Z}(t) = \bar{Z}\ \forall\ t \leq T_H \cap \breve{Z}(t) < \bar{Z}\ \forall\ t > T_H\}$*. Then*

1. $\frac{U'(\breve{R}(t))}{U'(\breve{R}(s))} > e^{-\rho(s-t)}$, $\forall\, t < T_H, s > t$;
2. $\frac{U'(\breve{R}(t))}{U'(\breve{R}(s))} = e^{-\rho(s-t)}$, $\forall\, t, s \geq T_H$;
3. $\exists\, T_X$, $0 < T_X < T_H$, *such that* $\breve{R}(t) = \bar{Z}/\varepsilon < \widetilde{R}(t)\ \forall\ t < T_X$; $\breve{R}(t) > \widetilde{R}(t)\ \forall\ t > T_X$;
4. $\breve{R}(t)$ *is continuous.*

Proof. Suppose $T_H = \infty$. Then $\breve{R}(t) = \bar{Z}/\varepsilon\,\forall\, t$. But then $\int_0^\infty \breve{R}(t)\mathrm{d}t = \infty > S_0$, which is infeasible. Hence T_H is finite. From the constraint and the definition of T_H follows that

$$\frac{U'(\breve{R}(t))}{U'(\breve{R}(s))} = 1 > e^{-\rho(s-t)},$$

for $t < s \leq T_H$. From (3.4) follows that $\breve{R}(t)$ is continuous at T_H, and declining from that instant onwards. This proves parts 1, 2 and 4.

Since $U' > 0$, not extracting some of the resource must be sub-optimal. Hence

$$\int_0^\infty \widetilde{R}(t)\mathrm{d}t = \int_0^\infty \breve{R}(t)\mathrm{d}t = S_0. \tag{3.9}$$

From part 1 of the lemma and part 2 of Lemma 3.1 follows that if $\breve{R}(t) \overset{<}{\underset{>}{=}} \tilde{R}(t)$ for some $t \geq T_H$, then $\breve{R}(t) \overset{<}{\underset{>}{=}} \tilde{R}(t)\ \forall\ t \geq T_H$. Then, since $\widetilde{R}(0) > \breve{R}(0) = \bar{Z}/\varepsilon$ and since $\tilde{R}(t)$ and $\breve{R}(t)$ are continuous, part 3 follows from (3.9). □

The extraction paths for the economies described in this section and in the previous section are illustrated by Figure 3.1. Initially, the path of extraction, and hence of emissions, of the initially constrained economy is below the extraction path of the unconstrained economy (more precise: the economy that never faces a binding emission constraint). The trajectories cross during the phase in which the former economy is still constrained, at $t = T_X$, and emissions from the unconstrained economy are, from then onwards, lower than emissions from the initially

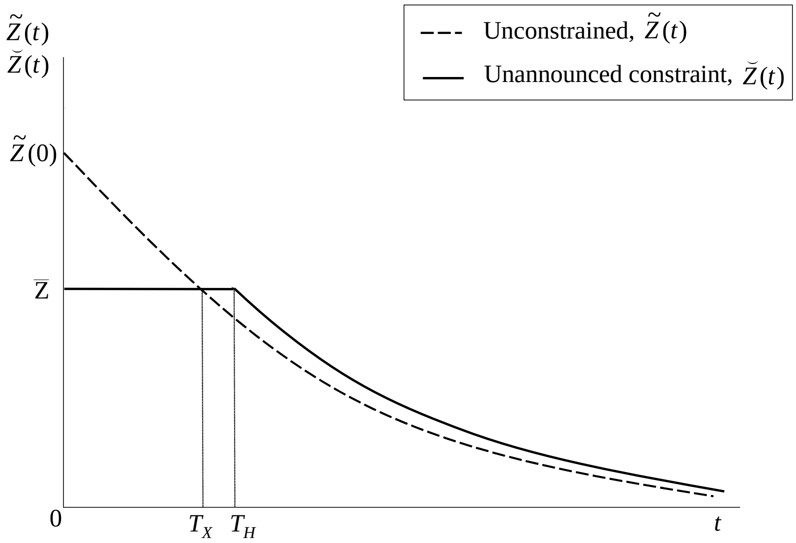

Figure 3.1: Emission paths for unconstrained economy, denoted $\tilde{Z}$, and of economy with same endowments but initially binding constraint, denoted $\breve{Z}$.

constrained economy. The intuition is quite simple. In both economies the entire resource stock has to be extracted over time, for otherwise intertemporal utility can be increased by simply extracting the remaining resource. Hence there is an 'abundance effect' as more of the resource becomes available for other periods: the initially constrained economy will have to extract more, compared to the unconstrained economy, at later points in time. Accordingly from T_X onwards emissions of the constrained economy are higher than emissions of the unconstrained economy.

3.4 An economy with an announced constraint

Now suppose that the constraint on emissions is announced at $t = 0$ but only becomes binding from $t = T > 0$ onward. As long as the economy is unconstrained, i.e. for all $t, s \in \{(0, T), [T_H, \infty)\}$, optimality requires (3.4) to hold. For all $t \in [T, T_H]$, we have $R(t) = \bar{Z}/\varepsilon$, and from Lemma 3.2 we know that extraction is continuous at $t = T_H$. The question remains, however, what the path of extraction is between announcement and the instant of implementation (the interim period).

Our first result concerns extraction at the instant of implementation:

Lemma 3.3. *Let* $\{Z(t) = \varepsilon R(t)\}_0^\infty$ *denote the path of emissions of the economy facing an announced emissions constraint* $Z(t) \leq \bar{Z} < \varepsilon\tilde{R}(T) \, \forall \, t \geq T > 0$*, as described in*

(3.1)-(3.3) *with* $T > 0$. *Then* $\lim_{t\uparrow T} R(t) > R(T) = \bar{Z}/\varepsilon$*: emissions and extraction jump down at* $t = T$.

Proof. Equation (3.4) must hold for any t and s that lie outside the interval $[T, T_H)$, and hence

$$\frac{U'(R(T^-))}{U'(R(T_H))} = e^{-\rho(T_H - T^-)} < 1,$$

where $R(T^-) \equiv \lim_{t\uparrow T} R(t)$. The constraint and the definition of T_H give $R(T) = \bar{Z}/\varepsilon = R(T_H)$, and hence $U'(R(T))/U'(R(T_H)) = 1$. Dividing the two fractions gives

$$\frac{U'(R(T^-))}{U'(R(T))} < 1.$$

Hence extraction and emissions must jump down at $t = T$. □

Before we can describe the entire path of extraction and emissions, we first need to know whether $R(0) \lesseqqgtr \widetilde{R}(0)$.

Lemma 3.4. $\varepsilon R(0) > \varepsilon \widetilde{R}(0)$*; that is, extraction and emissions jump up at the instant of announcement of a future binding emissions constraint.*

Proof. From Lemma 3.2, we know that $R(t) > \widetilde{R}(t)\,\forall\, t > T_H$ (note that the proof of Lemma 3.2 is independent of T being larger than or equal to zero). From (3.5) and the first step of the proof of Lemma 3.3 then follows that $R(t) > \widetilde{R}(t)\,\forall\, t < T$. □

We can now describe the optimal path of emissions and extraction in an economy with an announced constraint:

Proposition 3.1. *Suppose the economy described in* (3.1)-(3.3)*, faces an announced constraint on emissions (*$T > 0$*). Then*

1. *the level of emissions of this economy is initially higher than the level of emissions of the same economy when it would always be unconstrained ("the unconstrained economy");*
2. *emissions jump below the level of emissions of the unconstrained economy at the instant of implementation;*
3. *from the instant at which the constraint ceases to be binding onwards, the level of emissions is higher than the level of emissions of the unconstrained economy.*

Proof. Follows from Lemmas 1-4. An alternative proof is given in Appendix 3.A. □

We illustrate the emission path of the unconstrained economy and of the economy with an announced constraint in Figure 3.2. Initially, the level of emissions of the economy with an announced constraint is higher than the level of emissions of the economy without a constraint. This result can be interpreted as saying that the level of emissions jumps up at the instant of announcement. At the instant of implementation, emissions jump down, to a level that is below emissions of the unconstrained economy (for otherwise the constraint would not be binding). The path of extraction (emissions) of the unconstrained economy falls below the path of extraction (emissions) of the constrained economy during the period in which the latter is restricted in its emissions. When the constraint ceases to be binding, emissions and extraction of the constrained economy continue to be higher than those of the unconstrained economy.

As noted in the previous section, the entire resource stock must be extracted over time in both the unconstrained economy and in the economy with an announced ceiling on emissions. When the economy is constrained over some period of time, its extraction is less than what it would be without the constraint, and some of the resource is not extracted. This causes an abundance effect, as more of the resource is available to allocate over the periods in which the constraint is not binding. With an *un*announced constrained, all of the resource that is not extracted due to the constrained must be extracted later (see section 3.3). In the case of an announced constraint, however, the trade-off is to postpone extraction (and hence emissions), or to bring it forward. The solution to this trade-off is to do a bit of both. If all extraction were postponed, then this would give higher utility at future dates, which is then severely discounted. However, bringing all extraction forward implies low marginal utility at early dates. Indeed, it is optimal to equate discounted marginal utility in times that the constraint is not binding. As a consequence, some extraction is brought forward and some postponed, leading to an increase in emissions at the instant of announcement.

As the analysis shows that the optimal response to a future restriction on carbon dioxide emissions is an immediate *increase* in emissions, the short-run effect of announced climate policy goes directly against the policy's goal: although climate policy is aimed at postponing harmful emissions, such that the concentration of greenhouse gases does not become too high, the optimal reaction of resource owners and consumers to this policy is to initially extract and consume more compared to the status quo, thus increasing emissions.

A second surprising result is that at the instant of the policy's implementation, emissions and extraction (and hence utility) jump down. This is a surprising result, since it might be expected that risk-averse consumers smooth their consumption over time, as they know in advance of the binding constraint. However, consumption smoothing only takes place to the same extent as in an unconstrained econ-

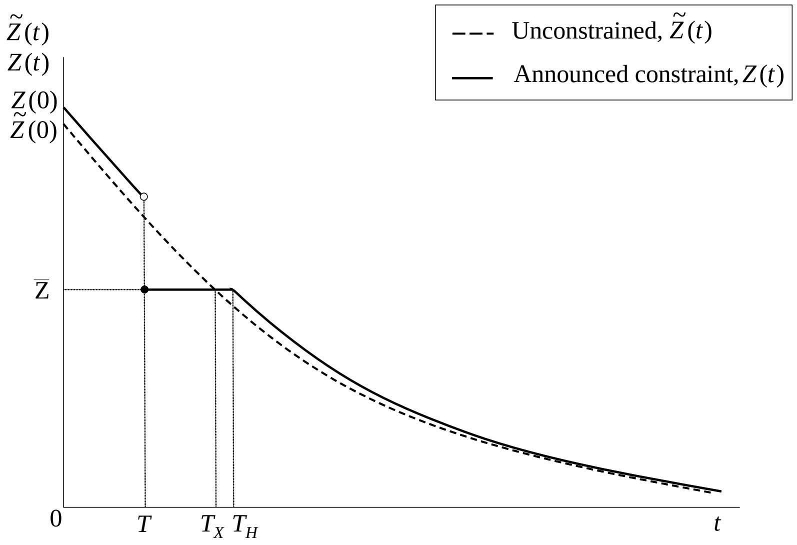

Figure 3.2: Emission paths for unconstrained economy, denoted $\tilde{Z}$, and of same economy but with announced emissions constraint, denoted Z.

omy: at any two points in time at which the economy is not restricted in its extraction, discounted marginal utility has to be equal. While the entire resource stock has to be extracted over time, a binding constraint for some period of time implies that less can be extracted during that period, and more has to be extracted during other periods. Consumption smoothing then implies that some of the 'additional' resource must be extracted before the constraint becomes binding, and some after the constraint ceases to be binding. At the instant at which the constraint becomes binding, consumers would like to smooth consumption by increasing extraction right after this instant, but due to the constraint they cannot.

In the coming sections we study how these results are affected by changes in preferences and policy.

3.5 Effects of changes in preferences and policy when the constraint is announced

The previous section not only showed that emissions will jump up at the instant of announcement, it also showed that extraction and consumption will jump down at the instant of implementation. That is, consumption is not fully smoothed during the interim period. These results summon several new questions themselves.

Does a higher willingness to smooth consumption reduce the downward jump in utility at the instant of implementation? How does a longer interim period affect the jumps, and how does it affect the instant at which the constraint ceases to be binding? These are some of the questions that will be discussed in this section.

3.5.1 Effects on the duration of the constraint

An announced constraint will lead to an upward jump in extraction and emissions at the instant of announcement, and a downward jump in both at the instant of implementation. In this section we study the effect (ceteris paribus) of a change in the willingness to smooth consumption (the coefficient of relative risk aversion), in the degree of patience of society ρ, and in the climate policy itself, both through a change in the instant of implementation T and a change in the tightness of the constraint, $\bar{Z}$.

Throughout this section, we assume a constant coefficient of relative risk aversion. That is, we assume that $\eta(R(t))$ in (3.6) is constant over time, and hence that the instantaneous utility function reads

$$U(t) = \begin{cases} \frac{R(t)^{1-\eta}-1}{1-\eta}, \ \eta \neq 1 \\ \ln R(t), \ \eta = 1 \end{cases} \tag{3.10}$$

When $\eta(R(t))$ is a constant, we can integrate (3.7), using $S(0) = S_0$, to find the extraction path of the economy described in (3.1)-(3.2) (i.e. the economy that is never constrained) in levels:

$$R(t) = \frac{\rho}{\eta} S(t) = \frac{\rho}{\eta} S_0 \mathrm{e}^{-\frac{\rho}{\eta} t}. \tag{3.11}$$

The total stock of emissions initially 'available' to the economy, εS_0, is allocated over the three periods of extraction:

$$\varepsilon S_0 = \int_0^T \varepsilon R(t) \mathrm{d}t + \int_T^{T_H} \varepsilon R(t) \mathrm{d}t + \int_{T_H}^{\infty} \varepsilon R(t) \mathrm{d}t. \tag{3.12}$$

Using $R(T_H) = \bar{Z}/\varepsilon$, the fact that (3.5) must hold for any t, s outside the interval $[T, T_H)$ so that (3.7) holds for any t outside this interval, and using the assumption that η is now a constant, we find

$$R(0) = \frac{\bar{Z}}{\varepsilon} \mathrm{e}^{\frac{\rho}{\eta} T_H}. \tag{3.13}$$

This can be used to solve the first integral in (3.12). From $t = T_H$ on, the economy is unconstrained. Hence, at this instant, (3.11) must hold with $R(T_H) = \bar{Z}/\varepsilon$, which can be used to solve the last integral. Noting that $\varepsilon R(t) = \bar{Z} \ \forall \ t \in [T, T_H]$ for the second part of (3.12), we can rewrite (3.12) as

$$\varepsilon S_0 = \frac{\eta}{\rho} \bar{Z} \mathrm{e}^{\frac{\rho}{\eta} T_H} \left(1 - \mathrm{e}^{-\frac{\rho}{\eta} T}\right) + (T_H - T)\bar{Z} + \frac{\eta}{\rho} \bar{Z}. \tag{3.14}$$

With this implicit function, we can derive the following result:

Proposition 3.2. *Changes in preferences and policy have the following effects on the length of the constrained period T_H:*

1. *The higher the coefficient of relative risk aversion η (ceteris paribus), or the lower the rate of time preference ρ (ceteris paribus), the shorter will be the duration of the constraint if* $\left(1-\frac{\rho}{\eta}T_H+\left(\frac{\rho}{\eta}(T_H-T)-1\right)\mathrm{e}^{-\frac{\rho}{\eta}T}\right)\mathrm{e}^{\frac{\rho}{\eta}T_H}+1>0$*, and the longer will be the duration of the constraint if* $\left(1-\frac{\rho}{\eta}T_H+\left(\frac{\rho}{\eta}(T_H-T)-1\right)\mathrm{e}^{-\frac{\rho}{\eta}T}\right)\mathrm{e}^{\frac{\rho}{\eta}T_H}+1<0$*;*

2. *The later the instant of implementation (a higher T), the shorter the duration of the constraint;*

3. *The looser the constraint (a higher $\bar{Z}$), the shorter the duration of the constraint.*

Proof.

$$\frac{\mathrm{d}T_H}{\mathrm{d}(\eta/\rho)}=-\frac{\bar{Z}\left(\left(1-\frac{\rho}{\eta}T_H+\left(\frac{\rho}{\eta}(T_H-T)-1\right)\mathrm{e}^{-\frac{\rho}{\eta}T}\right)\mathrm{e}^{\frac{\rho}{\eta}T_H}+1\right)}{\bar{Z}\left(\mathrm{e}^{\frac{\rho}{\eta}T_H}-\mathrm{e}^{\frac{\rho}{\eta}(T_H-T)}+1\right)}\lesseqgtr 0 \iff$$

$$\left(1-\frac{\rho}{\eta}T_H+\left(\frac{\rho}{\eta}(T_H-T)-1\right)\mathrm{e}^{-\frac{\rho}{\eta}T}\right)\mathrm{e}^{\frac{\rho}{\eta}T_H}+1\gtreqless 0 \tag{3.15}$$

$$\frac{\mathrm{d}T_H}{\mathrm{d}T}=-\frac{\mathrm{e}^{\frac{\rho}{\eta}(T_H-T)}-1}{\mathrm{e}^{\frac{\rho}{\eta}T_H}-\mathrm{e}^{\frac{\rho}{\eta}(T_H-T)}+1}<0; \tag{3.16}$$

$$\frac{\mathrm{d}T_H}{\mathrm{d}\bar{Z}}=-\frac{\frac{\eta}{\rho}\left(\mathrm{e}^{\frac{\rho}{\eta}T_H}-\mathrm{e}^{\frac{\rho}{\eta}(T_H-T)}\right)+T_H-T+\frac{\eta}{\rho}}{\bar{Z}\left(\mathrm{e}^{\frac{\rho}{\eta}T_H}-\mathrm{e}^{\frac{\rho}{\eta}(T_H-T)}+1\right)}<0. \tag{3.17}$$

□

A higher coefficient of relative risk aversion η (a lower rate of pure time preference ρ) has two effects on the duration of the constraint. First, it can be seen that the first part of (3.14) vanishes when $T=0$, in which case $\mathrm{d}T_H/\mathrm{d}(\eta/\rho)=-1$. In that case, discussed in section 3.3, an increase in η/ρ implies a higher (less negative) *growth rate* of extraction from T_H onwards (see (3.7)), as consumers are more patient and/or more willing to smooth consumption over time. This higher cumulative level of extraction in the period after the initial T_H has to be compensated by a decrease in T_H in order for total extraction to be feasible, given the initial stock. However, when $T>0$, a change in η/ρ has an additional opposing effect on the first term. Intuitively, the counter-effect is that an increase in η/ρ leads to a reduction in the *level* of extraction through $R(0)$ (see (3.13) and the first term in (3.14)). Note that initially (in the interim period) the growth rate of extraction is determined by (3.7), as can be seen by the term η/ρ in the first part of (3.14). Hence, there are two terms that positively affect the growth rate of extraction due to an increase in η/ρ, and one term that negatively affects the level of extraction, outside the constrained phase. Which of these two effects dominates, and hence in which direction T_H has to be adjusted for extraction to be both feasible and not to leave some of the resource in the ground, depends on the initial values of parameters.

An increase in T unambiguously leads to a shorter duration of the constraint. As more of the resource is extracted during the interim phase, the economy is at $S(t) = (\eta/\rho)\bar{Z}/\varepsilon$ sooner, and hence the period in which the economy is constrained is shorter.

A looser constraint also unambiguously leads to a shorter period in which the economy is constrained. The underlying intuition is the same as for the previous case: when $\bar{Z}$ is larger, the economy is at $S(t) = (\eta/\rho)\bar{Z}/\varepsilon$ sooner, and hence the period in which the economy is constrained is shorter.

3.5.2 Effects on the jumps in extraction and emissions

We now study how changes in preferences (η/ρ) and policy $(T, \bar{Z})$ affect the jumps in emissions at $t = 0$ and $t = T$.

Proposition 3.3. *Changes in preferences and policy have the following effects on the optimal path of emissions and extraction:*

1. *The higher the coefficient of relative risk aversion η (ceteris paribus), or the lower the rate of time preference ρ (ceteris paribus), the smaller will be both the size of the upward jump in emissions and extraction at $t = 0$ and the size of the downward jump in emissions and extraction at $t = T$;*

2. *The later the instant of implementation (a higher T), the smaller will be both the size of the upward jump in emissions and extraction at $t = 0$ and the size of the downward jump in emissions and extraction at $t = T$;*

3. *The looser the constraint (a higher $\bar{Z}$), the smaller will be both the size of the upward jump in emissions and extraction at $t = 0$ and the size of the downward jump in emissions and extraction at $t = T$.*

Proof. Substituting (3.13) into (3.14), we find:

$$\varepsilon S_0 = \frac{\eta}{\rho} Z(0)\left(1 - e^{-\frac{\rho}{\eta}T}\right) + (T_H - T)\bar{Z} + \frac{\eta}{\rho}\bar{Z}. \tag{3.18}$$

Use the implicit function theorem to find

$$\frac{\mathrm{d}Z(0)}{\mathrm{d}(\rho/\eta)} = -\frac{-\frac{\eta}{\rho}\left(\frac{\eta}{\rho}Z(0)\left(1-\mathrm{e}^{-\frac{\rho}{\eta}T}\right)+TZ(0)\mathrm{e}^{-\frac{\rho}{\eta}T}\right)+\frac{\eta}{\rho}\bar{Z}}{\frac{\eta}{\rho}\left(1-\mathrm{e}^{-\frac{\rho}{\eta}T}\right)+T_H-T} > 0; \tag{3.19}$$

$$\frac{\mathrm{d}Z(0)}{\mathrm{d}T} = -\frac{Z(0)\mathrm{e}^{-\frac{\rho}{\eta}T}-\bar{Z}}{\frac{\eta}{\rho}\left(1-\mathrm{e}^{-\frac{\rho}{\eta}T}\right)+T_H-T} < 0; \tag{3.20}$$

$$\frac{\mathrm{d}Z(0)}{\mathrm{d}\bar{Z}} = -\frac{\frac{\eta}{\rho}\left(\mathrm{e}^{\frac{\rho}{\eta}T_H}-\mathrm{e}^{\frac{\rho}{\eta}(T_H-T)}\right)+T_H-T+\frac{\eta}{\rho}}{\frac{\eta}{\rho}\left(1-\mathrm{e}^{-\frac{\rho}{\eta}T}\right)+T_H-T} < 0. \tag{3.21}$$

□

Although consumption smoothing cannot prevent a downward jump in extraction and utility at the instant of implementation, the size of the jump is negatively affected by the willingness to smooth. That is, the higher the coefficient of relative risk aversion η, the smaller is the jump at $t = T$. Furthermore, the jump is smaller when society is more patient (smaller ρ). At the same time, the higher is η (or the smaller is ρ), the smaller is the upward jump in utility and emissions at the instant of announcement $t = 0$. These results are as expected, as a higher η (smaller ρ) implies a lower willingness to accept changes in utility, that is one would prefer a flatter extraction path over time. An increase in this willingness not only leads to smaller jumps at the instants of announcement and implementation, but also to a flatter extraction path in the interim period. However, as Proposition 3.1 shows, the two jumps occur irrespective the size of η and ρ.

The second part of Proposition 3.3 shows that a longer interim period, i.e. a longer period between the instant of announcement and the instant of implementation of the policy, leads to smaller jumps in utility and emissions at $t = 0$ and $t = T$. Indeed, a longer interim period gives the economy time to burn some of the resources, leading to a lower stock and hence lower unconstrained emissions just before the instant at which the constraint becomes binding (see (3.11)). This in turn reduces the pressure to increase extraction (compared to an economy that is always unconstrained) in the interim period; this pressure comes from the fact that it is optimal to extract the entire resource stock over time. When an economy faces some period in which it is constrained in its extraction, it will need to *increase* extraction during another period in order to still extract the entire stock.

Part 3 of the proposition states that a looser constraint (i.e. an increase in $\bar{Z}$) leads to smaller jumps at announcement and implementation of the policy. With a looser constraint, the difference between unconstrained emissions and constrained emissions is smaller, and hence the jump at the instant of implementation is smaller. In addition, a looser constraint implies less need to increase emissions during the interim phase (in order to extract the entire resource stock), and hence a smaller upward jump in emissions and extraction at the instant of announcement.

3.6 Conclusions

Announcing climate policy in advance gives firms time to adjust, and can therefore lower the overall burden of the policy on the economy. In this chapter, we have studied the effect of pre-announcement of a ceiling on carbon dioxide emissions ("Kyoto forever") on emissions in the period between the policy's announcement and its implementation. When carbon emissions come from a non-renewable resource like coal or oil, climate policy will affect the optimal path of extraction and emissions.

Our first result is that announcement of the policy induces an *increase* emissions at the instant of announcement. This increase in emissions is due to an increase in extraction, which in turn comes from an abundance effect. The ceiling on emissions directly causes a reduction in extraction during some period of time. As it is optimal to extract the entire resource stock over time, the difference between this restricted emissions and the optimal path has then to be extracted either after the instant at which optimal unrestricted emissions equal the level of the ceiling, or between the instants of announcement and implementation. Proposition 3.1 states that the solution is to do a bit of both. Postponing all extraction implies high levels of utility in the future, which are then severely discounted, while extracting all of the 'extra' resource before the constraint becomes binding brings along low levels of marginal utility in comparison with a more gradual extraction path. As a consequence, resource extraction and emissions increase at the instant of the policy's announcement. As the idea underlying the policy is to stabilize the concentration of carbon dioxide in the atmosphere (Article 2 of the UNFCCC), this emissions increase goes directly *against* the spirit of the policy. Hence, there seems to be a trade-off between the economic gain of pre-announcement of climate policy, and the environmental loss coming from it. For future research it would be interesting to include a second resource in the model (as in chapter 2 of this thesis, but then focussing on extraction and emission *levels*), to study whether substitution effects will enhance or mitigate the abundance effect we found in this chapter.

In addition we show that, although emissions and extraction jump *up* at the instant of announcement of climate policy, both jump *down* at the instant of implementation. That is, even when climate policy is announced some years in advance, consumption will not be smoothed to avoid a jump in utility at the instant at which the constraint is put into practice. The upwards force on extraction in the interim phase, from being able to benefit from resource use while not yet being constrained, outweighs the possible benefit from avoiding a downward jump in utility. However, we show that some consumption smoothing does take place: the higher the coefficient of risk aversion, the smaller the initial upward jump and the smaller the downward jump in utility at the instant of implementation. The possibility of a downward jump in utility, even when the policy is announced in advance, is intriguing, and deserves further research. For example, when emission reductions in the interim period can be banked for use during the constrained period, this jump might disappear as the prices of the two periods are then linked. This brings an opportunity cost for emissions in the interim period.

We also show that a longer interim period and a looser constraint reduce the sizes of both jumps. Furthermore, the length of the period in which the economy is constrained is shorter if the coefficient of relative risk aversion is higher, the interim period is longer, and the constraint is looser.

The key message of this chapter is that there is a trade-off between the economic gain from pre-announcing a ceiling on carbon dioxide emissions, and the environmental loss stemming from an increase in emissions in the period between announcement and implementation. The shorter the interim period, the larger will be the instantaneous effect. Of course, immediate implementation postpones emissions until the constraint ceases to be binding, which is the main purpose of climate policy. This lesson should be taken into account by countries that do not yet have a binding constraint on carbon dioxide emissions.

3.A Appendix: Solving the problem of an announced constraint with a Hamiltonian

In this Appendix we study the same problem as in the main text, but using a different approach to solve the problem.

3.A.1 The model

Again, consumers maximize intertemporal utility, while instantaneous utility U (which is a $\mathscr{C}^2$ function such that $U' > 0$ and $U'' < 0$) comes from the use of a nonrenewable resource. One unit of resource use causes ε units of emissions of carbon dioxide Z. At some point in time $T \geq 0$, the economy faces a ceiling on the amount of emissions, denoted by $\bar{Z}$.

$$\max_{\{R(t)\}_0^\infty} \int_0^\infty U(R(t))\mathrm{e}^{-\rho t}\mathrm{d}t; \tag{3.22}$$

$$\dot{S}(t) = -R(t),\ R(t) \geq 0,\ S(0) = S_0; \tag{3.23}$$

$$Z(t) \equiv \varepsilon R(t) \leq \bar{Z}\ \forall t \geq T; \tag{3.24}$$

$R(t)$ denotes extraction of the nonrenewable at time t, and ρ is the rate of time preference. Equation (3.23) shows that the stock S of the nonrenewable declines with extraction (we define, for any variable x, $\dot{x} \equiv \mathrm{d}x/\mathrm{d}t$). The initial endowment of the resource, S_0, is finite and given. Climate policy is described in (3.24): emissions Z arise from resource use, but starting at time T, they cannot exceed $\bar{Z}$ (i.e., we put a constraint on the control variable R).

Since the constraint is announced in advance, the planning horizon is divided in two phases: a first period when the constraint is not yet enforced (the *interim phase*), and a second period when the constraint is enforced and (at least initially) binding (the *enforcement phase*). The problem in (3.22)-(3.24) is therefore an infinite-horizon discounted two-stage optimal control problem, with a fixed switching time at $t = T$.

The Lagrangians for the two stages of the problem are:

$$\mathscr{L}^1(\cdot) = U(R(t)) - \lambda^1(t)R(t) + \gamma^1(t)R(t); \tag{3.25}$$

$$\mathscr{L}^2(\cdot) = U(R(t)) - \lambda^2(t)R(t) + \gamma^2(t)R(t) + \tau(t)\left(\bar{Z} - \varepsilon R(t)\right); \tag{3.26}$$

where superscript 1 indicates the Lagrangian covering the period $t \in [0, T)$ and 2 indicates the Lagrangian covering $t \geq T$. Furthermore, λ is the co-state variable associated to (3.23), γ is the multiplier for the nonnegativity constraint on the extraction rate, and τ is the multiplier associated with the emission constraint.

Makris (2001) shows that for this problem the standard first-order conditions from optimal control theory,[25]

$$U'(R(t)) = \lambda^j(t) - \gamma^j(t) + \varepsilon\tau(t), \tag{3.27}$$

$$\dot{\lambda}^j(t) = \rho\lambda^j(t); \tag{3.28}$$

where $j \in \{1,2\}$, need to be complemented by the following matching condition for the co-state variable in the two stages:

$$\lambda^1(T) = \lambda^2(T). \tag{3.29}$$

This guarantees the continuity of the co-state variable at the time of the switch. For the remainder of the chapter we therefore drop the superscripts to λ.

The complementary slackness conditions for the constraints are,

$$\tau(t) \geq 0,\ \bar{Z} - Z(t) \geq 0,\ \tau(t)\left[\bar{Z} - Z(t)\right] = 0,\ \forall t \geq T; \tag{3.30}$$

$$\gamma^j(t) \geq 0,\ R(t) \geq 0,\ \gamma^j(t)R(t) = 0; \tag{3.31}$$

and transversality condition reads,

$$\lim_{t\to\infty} \lambda(t)S(t)\,\mathrm{e}^{-\rho t} = 0. \tag{3.32}$$

3.A.2 The laissez faire economy

In this section we look at the economy described above, focussing on the case in which the constraint never binds ($\bar{Z} \to \infty$ and $\tau(t) = 0$). This we call the *laissez faire* economy as government policy does not influence the agent's choices. Denote by $\tilde{x}$ the value of variable x for a laissez faire economy.

As can be seen from (3.27) and (3.28), marginal utility along the optimal trajectory grows in parallel with the scarcity rent $\tilde{\lambda}$ at rate ρ. At each point in time, total extraction equals energy demand, and is simply given by $\tilde{R}(t) = d(\tilde{\lambda}(t)) \equiv U'^{-1}(\tilde{\lambda}(t))$. Thus, extraction is continuous and declines along the optimal path.

From (3.32) and (3.28) follows that the entire resource stock gets extracted over time. The initial scarcity rent $\tilde{\lambda}(0)$ then solves $\int_0^\infty d\left(\tilde{\lambda}(0)e^{\rho t}\right)\mathrm{d}t = S_0$. Hence, the larger the initial (total) resource stock, the lower $\tilde{\lambda}(0)$, and the higher initial extraction (see (3.27)).

3.A.3 The optimal path of energy consumption: the abundance effect

We now study the optimal path of energy consumption R in the presence of an announced and binding emission constraint $\bar{Z}$. Suppose that the constraint on

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[25] In the interest of compactness, and with a slight abuse of notation, we have indicated the necessary conditions for the two stages as one. Note that $\tau(t) = 0$ for all $t < T$.

emissions is announced at $t = 0$ but only becomes binding from $t = T > 0$ onward. We denote the (endogenous) instant at which the constraint ceases to be binding by T_H.

In the previous section we have shown that as long as the economy is unconstrained, i.e. for all $t \in \{(0, T), [T_H, \infty)\}$, marginal utility grows at rate ρ. From (3.29) then follows that $U'(t)\mathrm{e}^{-\rho t} = U'(s)\mathrm{e}^{-\rho s}$ for $t, s \in (0, T)$ and $t, s \in [T_H, \infty)$. The question remains, however, what the path of extraction is between announcement and the instant of implementation (the interim phase).

Lemma 3.5. *Suppose an emission constraint is announced at* $t = 0$ *and becomes binding at* $t = T > 0$. *Then energy use jumps up at the instant of announcement due to an* abundance effect.

Proof. By definition of a binding emissions constraint, $U(R(T)) < U(\tilde{R}(T))$ and hence $R(T) < \tilde{R}(T)$. Hence, during some strictly positive period of time, $R(t) < \tilde{R}(t)$. From (3.32) and (3.28) then follows that during other periods $R(t) > \tilde{R}(t)$, as energy becomes more abundant for the rest of the time horizon. Since for all $t, s \in \{(0, T), [T_H, \infty)\}$, marginal utility grows at rate ρ, and since $U'(t)\mathrm{e}^{-\rho t} = U'(s)\mathrm{e}^{-\rho s}$ for $t \in (0, T)$ and $s \in [T_H, \infty)$, it follows that if $U'(R(t))e^{-\rho t} \gtrless U'(\tilde{R}(t))e^{-\rho t}$ for some $t \in \{(0, T), [T_H, \infty)\}$, then this is the case for all $t \in \{(0, T), [T_H, \infty)\}$. Suppose $U'(R(t))e^{-\rho t} \geq U'(\tilde{R}(t))e^{-\rho t}$ at some $t \in \{(0, T), [T_H, \infty)\}$. Then $R(t) \leq \tilde{R}(t) \forall t \in \{(0, T), [T_H, \infty)\}$. Since energy extraction must be continuous at T_H (for otherwise the Hamiltonian $U(R(t)) - \lambda(t)R(t)$ in (3.26) is not continuous, which cannot be optimal), and since $R(T) < \tilde{R}(T)$, the transversality condition is violated. Hence $R(t) > \tilde{R}(t) \forall t \in \{(0, T), [T_H, \infty)\}$. □

From this proof follows the following result:

Corollary 3.1. *Suppose an emission constraint is announced at* $t = 0$ *and becomes binding at* $t = T > 0$. *Then energy use, utility, and the value of the Hamiltonian jump down at* $t = T$.

As shown in Makris (2001), a special feature of a two-stage optimal control problem with a fixed switching point is the possibility of a jump in the value of the Hamiltonian at the switching point. When the switching point T is at the interior of the interval $(0, \infty)$, the Hamiltonian will jump down, as is the case in our model.

From (3.32) and (3.28), continuity of extraction and $U'(t)\mathrm{e}^{-\rho t} = U'(s)\mathrm{e}^{-\rho s}$ for $t, s \in (0, T)$ and $t, s \in [T_H, \infty)$ follows that $\exists T_X$ such that $Z(t) = \bar{Z} < \widetilde{Z}(t)\ \forall\ t \in [T, T_X)$; $Z(T_X) = \bar{Z} = \widetilde{Z}(T_X)$; and $Z(t) = \bar{Z} > \widetilde{Z}(t)\ \forall\ t \in (T_X, T_H]$.

We summarize our results in the following proposition:

Proposition 3.4. *Let* $\widetilde{Z}(t) = \varepsilon\widetilde{R}(t)$ *denote carbon dioxide emissions of an economy that will always be unconstrained in its emissions, and let* $Z(t) = \varepsilon R(t)$ *denote emissions of an economy that is constrained for some period of time. Then the optimal path of emissions in an economy with an announced emissions constraint, as described in* (3.22)-(3.24)*, evolves as follows:*

1. $Z(t) > \widetilde{Z}(t) > \bar{Z}\ \forall\, 0 \leq t < T;$
2. $Z(t) = \bar{Z} < \widetilde{Z}(t)\ \forall\, t \in [T, T_X);$
3. $Z(T_X) = \bar{Z} = \widetilde{Z}(T_X);$
4. $Z(t) = \bar{Z} > \widetilde{Z}(t)\ \forall\, t \in (T_X, T_H];$
5. $\widetilde{Z}(t) < Z(t) < \bar{Z}\ \forall\, t > T_H.$

Proof. In text. □

Part II

Climate policy, input substitution, and technological change

CHAPTER 4

Carbon leakage revisited: unilateral climate policy with directed technical change[26]

An important threat to climate policy is that actions undertaken without universal participation may prove to be ineffective: any partial agreement to reduce emissions, of carbon dioxide (CO_2) for example, may be undermined by the behaviour of countries outside the agreement. Indeed, increases in CO_2 emissions by unconstrained countries can off-set the reductions secured by the agreement participants, a phenomenon known as *carbon leakage*.[27]

The behaviour of unconstrained countries in reaction to a reduction of CO_2 emissions of other countries is mainly driven by two economic mechanisms. First, when the production of energy-intensive goods is reduced in constrained countries due to the introduction of an emission constraint, the international prices of such goods will increase. This gives countries outside the abating coalition incentives to expand their production of these goods and export them to signatory coun-

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[26] This chapter is a slightly adjusted reprint of Di Maria and van der Werf (2008). We are greatly indebted to Sjak Smulders, Emiliya Lazarova and Maurizio Zanardi for fruitful discussions. We would also like to thank Erwin Bulte, Henk Folmer, Cees Withagen, Aart de Zeeuw, conference participants in Zürich, Bremen and Amsterdam, and two anonymous referees for useful comments.

[27] Estimates of the size of this effect rely on Computable General Equilibrium (CGE) models. The leakage rates for the Kyoto Protocol (the percentage of the reduction in emissions offset by the increase in emissions by countries outside the Protocol) reported in the literature range from 2% to 41% (see for example Burniaux and Oliveira Martins, 2000, Light et al., 2000). Babiker (2005) even finds a leakage rate of 130% for one of his scenarios. These differences in the estimates stem from widely differing assumptions with respect to the degree of international market integration, substitution and supply elasticities, and market structure.

tries (the *terms-of-trade* effect). Clearly, this implies an increase in emissions by countries outside the agreement. The second mechanism of carbon leakage works through the price of fossil fuels: as the price of fossil fuels decreases following the reduction in demand on the part of the constrained countries, countries outside the agreement might decide to substitute other inputs with fossil fuels, thus increasing their emissions (the *energy-market* effect).

In sum, climate change policy affects the relative prices of both goods and factors, thus inducing the leakage of carbon emissions. These price changes, however, also modify the incentives for innovation, changing the level and, most importantly, the direction of technological change (i.e. how technology levels develop across industries). This effect, known as induced technological change, was already postulated by Hicks (1932), and has since been the focus of many influential contributions, both theoretical and empirical.[28] Once the available technology changes as a result of climate policy, however, so do the responses of the unconstrained countries. Yet, this additional mechanism has to date been almost completely ignored in the climate change policy literature.[29]

In this chapter, we study the consequences of induced (directed) technological change on carbon leakage using a stylized theoretical model of the interactions between constrained and unconstrained countries, which focuses on transmission mechanisms based on terms-of-trade effects. In order to be able to highlight the effects of induced technological change, we model two countries that are perfectly symmetric as refers to preferences, technology and endowments. In this way we rule out any other potential source of carbon leakage, which would cloud the effects of technological change. Indeed, we only allow the two countries to differ in one crucial respect: one country imposes a binding emission cap, while the other remains unconstrained. As the countries are symmetric before the imposition of the cap, the adjustment process represents a pure response to policy. In this sense, the chapter analyzes a 'policy-induced pollution-haven effect'.

To single out the contribution of technological change in the adjustment process,

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[28] For early contributions, see Kennedy (1964) and Drandakis and Phelps (1966). Recently, Acemoglu 1998, 2002 has provided a tractable theoretical framework to investigate the issue. Among the empirical contributions, Newell et al. (1999) study the effect of energy prices and government regulations on energy-efficiency innovation. They show that changes in energy prices affect the direction of innovation for some products, and induce changes in the subset of models offered for sale. They conclude that "the endogeneity of the direction, or composition of technological change is surely at least as significant [as] the overall pace of technological change" (p. 971). Popp (2002) shows that changes in energy prices (including the effects of environmental policy) positively and quickly affect environmentally friendly innovations.

[29] Grubb et al. (1995) first noted the importance of induced technological change for carbon leakage. However, in their paper induced technological change does not come from profit-maximizing behaviour. Instead, it is assumed to occur through an exogenous decrease in the emissions intensity of non-abating countries, following the decrease in emissions intensity in abating countries.

our analysis proceeds in two steps. We start from a situation of complete symmetry and analyze the effect of introducing an exogenous emission cap. The first step refers to analyzing a model where unilateral climate policy induces trade (in either energy-intensive goods, or directly in energy), but (the composition of) technology does not change. This is what we call the 'undirected technical change' scenario, where purely trade effects are at work. We then compare this benchmark to the case where technology levels of the labour- and energy-intensive industries are allowed to develop at different rates, i.e. the 'directed technical change' scenario. We show that, when (the composition of) technology is allowed to adjust endogenously, induced technological change always leads to a reduction in the degree of carbon leakage. We refer to this as the *induced-technology* effect.

This chapter contributes to the theoretical literature on carbon leakage by highlighting the role of directed technical change in this framework. The early literature on the topic addressed asymmetric international environmental policy from a public economics point of view (e.g. Hoel, 1991, Barrett, 1994, Carraro and Siniscalco, 1998). Stressing the roles of free-riding incentives and strategic behaviour among nations, but abstracting from both technical change and international trade, this literature concludes that emissions among countries are strategic substitutes and that unilateral climate policy will lead to leakage of emissions. More recently, however, Copeland and Taylor (2005) show that in the presence of international trade and environmental preferences, a country's response to a rest-of-world emissions reduction is ambiguous: emissions among countries can be either strategic complements or substitutes depending on key elasticities in the model. In their static two-good, two-factor, K-country model without technical change, this result follows from allowing for income and substitution effects on the consumption side to offset the terms-of-trade effect on the production side. The mechanism underlying their result therefore differs from ours, both in terms of modelling and in terms of economic content.

Closer in spirit to our work, Golombek and Hoel (2004) study the effect of international spillovers of abatement technology on leakage, using a static partial equilibrium two-country, one-good model with transboundary pollution. In each country a central planner chooses research and development (R&D) expenditures and abatement levels to minimize total costs that include environmental damages. Research activities lead, by assumption, to reductions in abatement costs, while international technology spill-overs allow technology to diffuse across borders at no cost. Hence, the authors effectively build in their model a mechanism that counteracts the free-riding incentives underlined by previous literature. In our model, on the other hand, the nature of technical change is endogenous, as it is itself driven by profit incentives, and depends on the characteristics of production.

The rest of the chapter develops as follows. We introduce the model in section 4.1

and present the key equilibrium conditions in section 4.2. Section 4.3 contains the main results of the chapter. Here we first introduce the terms-of-trade effect and study carbon leakage when entrepreneurs cannot aim new technologies to one of the sectors; we then focus on carbon leakage under directed technical change and show how the induced-technology effect changes the previous results. In section 4.4 we discuss how our results relate to the existing literature and conclude, pointing at possible extensions.

4.1 The Model

Our economy consists of two countries, c and u, that have identical production technologies and endowments, while only differing in their environmental policies. We focus on a situation of free trade noting that, as long as the two countries do not differ in environmental policies, there will be no actual scope for trade. We assume that country c (for *constrained*) imposes an exogenously imposed binding cap on polluting emissions. By imposing an exogenous constraint, rather than modelling asymmetries in (environmental) preferences, we are able to identify the pure effect of technological change on carbon leakage. If we were, instead, to assume differences in preferences across countries, we would introduce additional (asymmetric) effects through income and substitution mechanisms. In this case, however, it would be impossible to isolate and emphasize the role of directed technical change in the final outcome. Since the focus of this chapter is on carbon leakage, we do not discuss economic growth or welfare, as such we do not need to solve explicitly for the interest rate. Moreover, consumption only occurs in terms of the final good and hence does not affect the relative demand for the intermediate goods, thus, we can abstract from the consumer's side of the economy altogether.

In each country, final output Y is obtained as a CES aggregate of two (intermediate) goods, Y_E and Y_L, with an elasticity of substitution equal to ε:

$$Y^r = \left[\left(Y_E^r\right)^{\frac{\varepsilon-1}{\varepsilon}} + \left(Y_L^r\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \tag{4.1}$$

where $r = c, u$ is the country index.[30] We assume that good Y_E is produced using energy (E) and a specialized set of differentiated machines. The range of types of machines available to produce energy intensive goods is indicated by N_E. Instead, Y_L is produced using labour (L_L) and a different set of machines, whose range is

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[30] For simplicity, we set the share parameters in the CES to one, as they will only introduce an additional constant term in the expressions. The choice of this specific functional form is done for tractability. However, as shown in Acemoglu (2007), the results pertaining to the bias of technical change are applicable to any production function featuring factor-augmenting technical change.

indicated by N_L. Following Acemoglu (2002), the production functions for the intermediate goods are as follows:

$$Y_E^r = \frac{1}{1-\beta}\left(\int_0^{N_E} k_E^r(i)^{(1-\beta)}di\right)\left(E^r\right)^{\beta}, \tag{4.2}$$

and

$$Y_L^r = \frac{1}{1-\beta}\left(\int_0^{N_L} k_L^r(i)^{(1-\beta)}di\right)\left(L_L^r\right)^{\beta}, \tag{4.3}$$

where $\beta \in (0,1)$ and $k_j^r(i)$ is the amount of machines of type i employed in sector $j = E, L$ in country r.

To produce each type of machine, producers need a blueprint invented by the R&D sector, as will be discussed below. We assume that machines developed to complement one factor of production cannot be usefully employed in the other sector and that blueprints can be traded internationally. Accordingly, N_E and N_L represent global levels of technology and producers in each country can use all machine types globally available for their sector.

We assume that in each country an amount of labour equal to $\overline{L}$ is inelastically supplied at each point in time, and that it is immobile across countries. Labour can either be employed in the production of the labour intensive good Y_L, or in the production of energy:

$$\overline{L} = L_L^r + L_E^r, \tag{4.4}$$

where L_E^r is the amount of labour in energy production in country r. As in Babiker (2005), we assume that energy has to be produced using labour and some fixed factor. Consequently there are decreasing returns to labour in energy production:

$$E^r = \left(L_E^r\right)^{\phi}, \tag{4.5}$$

where $\phi \in (0,1)$. Energy generation causes emissions of carbon dioxide. We assume that CO_2 emissions, Z, are proportional to the amount of energy produced, so that $Z = E$.

When country c introduces a binding constraint on the amount of carbon dioxide emitted, it *de facto* imposes a cap on the amount of labour allocated to energy production. Indeed, when Z^c is the maximum amount of emissions permitted at any point in time, the allocation of labour in country c must satisfy $L_E^c = (Z^c)^{1/\phi}$.

The last part of our model consists of the process of technical change. As mentioned in the introduction, in our analysis we aim at comparing the outcomes obtained under two alternative technology regimes: 'directed' and 'undirected' technical change (DTC and UTC, respectively henceforth).

Under *directed* technical change, prospective innovators decide on the amount of their R&D outlays, and are also able to choose the sector they want to target their innovation efforts to. They know from the onset which intermediate sector will use their innovation. Hence, they will invent new machines for the sector that promises the highest returns. Using a lab-equipment specification for the process of technical change, we assume that investing one unit of the final good in R&D generates v new innovations in any of the two sectors.[31] Thus, the development of new types of machines takes place according to the following production functions:[32]

$$\begin{aligned}\dot{N}_E &= v\left(R_E^c + R_E^u\right), \text{and} \qquad (4.6)\\ \dot{N}_L &= v\left(R_L^c + R_L^u\right), \qquad (4.7)\end{aligned}$$

where R_j^r indicates R&D expenditure in country r, and sector j, while a dot on a variable represents its time derivative, i.e. $\dot{x} = \mathrm{d}x/\mathrm{d}t$.

In order to have a meaningful comparison for the DTC regime, we model the following variant, that we call *undirected* technical change (UTC). In this case, prospective innovators invest in the development of blueprints whenever it is profitable to do so, yet they cannot choose the sector they want to develop a new machine for. We are thus able to emphasize the effect of the 'directedness' of technical change on carbon leakage, while technological change is endogenous in both versions. We imagine that with UTC the outcome of the R&D investment is uncertain in the sense that innovators are not sure in which sector their blueprint will find utilization, and hence they maximize expected, rather than certain, profits from R&D. To keep matters simple, we assume that the newly developed blueprint will be energy-complementing with probability $\gamma \in (0,1)$, and labour-complementing with probability $(1-\gamma)$. Consequently, the (expected) relative marginal productivity is constant, as is common in traditional (one-sector) models of endogenous growth.[33] As innovators can only determine the total outlays in R&D activities, but not the sectoral split, the total number of innovations develops according to:

$$\dot{N} = v\left(R^c + R^u\right), \qquad (4.8)$$

where R^r indicates total R&D investment by country r.

In both versions of the model, a new blueprint must be developed before the innovator can sell it to producers, thus the costs of R&D are sunk. Hence, machine producers must wield some monopoly power in the market for machines, in order

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[31] See Rivera-Batiz and Romer (1991) for the lab-equipment model.

[32] For simplicity, we assume that R&D is equally productive in the two sectors. Relaxing this assumption introduces a constant in the expressions that follow, but does not alter our qualitative results.

[33] With undirected technical change the relative level of technology in the two sectors, N_E/N_L, is exogenous and constant. Moreover, since N_E/N_L equals $\gamma/(1-\gamma)$, any value of N_E/N_L can be calibrated by an appropriate choice of the probability γ.

to recoup the development costs. For this we assume that an innovator is awarded a global patent for her invention and that patents are perfectly enforced in both countries. Thus, each innovation takes place only once, and no international overlap in blueprints occurs.[34]

Finally, we simplify the analysis by assuming that machine production is local, that is innovators license their blueprints to one producer in each region, so that blueprints are traded across countries, but machines are not.

4.2 Equilibrium

The main focus of the chapter is on the level of carbon emissions in both countries. As emissions are proportional to the amount of energy produced in each region, the key to derive the results in the following section is to understand the allocation of labour between production of the labour-intensive good Y_L, and energy. Appendix 4.A presents the complete solution of the model, here we only highlight some key elements of the solution.

In the intermediate goods' sectors, profit maximization entails the following first-order conditions:

$$w_E^r = \frac{\beta}{1-\beta}\left(p_E^r\right)^{1/\beta} N_E, \text{ and} \tag{4.9}$$

$$w_L^r = \frac{\beta}{1-\beta}\left(p_L^r\right)^{1/\beta} N_L; \tag{4.10}$$

where w_j^r is the price of input j, and p_j^r the price of intermediate Y_j, in country r. These equations allow a brief discussion of international trade in our model. Considering (4.9) and (4.10), it is immediate that goods' and factors' price equalization always obtains in our model. Consider first the case where no emission ceiling is imposed. Trivially, in this case the two countries are identical and all prices are the same across regions. Now, consider what happens when country c introduces an emission cap. The prices of both energy and the energy-intensive good tend to increase, creating the scope for trade. The constrained country exports the labour-intensive good, Y_L, against imports of Y_E and/or E. However, it is immaterial which of these goods is actually imported. Indeed, from (4.9) and (4.10), as long as p_L and *either* p_E *or* w_E are the same across countries, which follows from the law of one

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[34] Our focus in the current chapter is on the interaction between two highly developed countries, or coalitions thereof. To fix ideas one can think of the European Union as country c, and the United States as country u. In this context, it is natural to assume that patents are perfectly enforced internationally. Di Maria and Smulders (2004), instead, present a North-South trade model featuring directed technical change. There, the central assumption is that the protection of intellectual property rights is asymmetric, with patents being protected only in the developed North.

price, all prices equalize. In this sense, it makes no difference to allow for trade in energy-intensive goods, or directly in energy. Since prices always equalize, we drop the country index when this does not induce confusion.

Taking the ratio of the first-order conditions above, and using the expression for equilibrium prices – (4.24) in Appendix 4.A – we get the following expression for the relative factor rewards, $w \equiv w_E / w_L$, for given technology

$$w = N^{(\sigma-1)/\sigma} \left(S^w\right)^{-1/\sigma}, \tag{4.11}$$

where $N \equiv N_E / N_L$ is the 'technology ratio', $S^w \equiv (E^c + E^u) / \left(L_L^c + L_L^u\right)$ is the global (or world, hence the superscript w) relative factor supply, and $\sigma \equiv 1 + (\varepsilon - 1)\beta$. Solving (4.11) for S^w gives $S^w = N^{\sigma-1} w^{-\sigma}$, elucidating the role of σ as the elasticity of relative factor demand with respect to their relative price. Hence, the relative price of energy decreases with energy supply, while, as will be discussed later, the effect of changes in the technology ratio N on relative factor rewards depends on whether the relative energy demand is elastic or inelastic.[35]

In the energy sector, producers employ labour, L_E^r, so as to satisfy the first-order condition for profit maximization $w = \left(L_E^r\right)^{1-\phi} / \phi$. Equating this to (4.11) yields the following expression:

$$\phi^{-\sigma} N^{1-\sigma} L_E^{\phi(1-\sigma)+\sigma} + L_E = \overline{L}. \tag{4.12}$$

Here $L_E = L_E^c = L_E^u$ is the amount of labour employed in energy production in each country, when both countries are unconstrained, and technology N is given.

When country c faces a binding emission constraint, its emissions, energy generation and amount of labour in energy production are determined by the cap: $L_E^c = (Z^c)^{1/\phi}$. In the unconstrained country however, energy producers still choose the amount of labour so as to maximize profits. Taking the value of the cap into account, we find the following expression representing the equilibrium allocation of labour in country u, for given N and L_E^c:

$$\phi^{-\sigma} N^{1-\sigma} \left[\left(L_E^c\right)^{\phi} \left(L_E^u\right)^{\sigma(1-\phi)} + \left(L_E^u\right)^{\phi(1-\sigma)+\sigma} \right] + L_E^c + L_E^u = 2\overline{L}. \tag{4.13}$$

So far we have assumed that N is constant, in accordance with our definition of undirected technical change. When technical change is directed, instead, innovators choose (the amount and) the direction of their innovation efforts. They will invest in the sector which is expected to yield the highest rate of return. In Appendix 4.A, we show that the relative profitability of innovations in the two sectors, $\pi = \pi_E / \pi_L$ is given by:

$$\pi = p^{1/\beta} S^w,$$

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[35] Since $\sigma \equiv 1 + (\varepsilon - 1)\beta$, it follows that $\sigma \gtrless 1 \Leftrightarrow \varepsilon \gtrless 1$. Thus, the relative factor demand is elastic ($\sigma > 1$) if and only if intermediate goods are gross substitutes in the production of the final good ($\varepsilon > 1$), and inelastic ($\sigma < 1$) if and only if they are gross complements ($\varepsilon < 1$).

where $p \equiv p_E/p_L$. At each point in time, the direction of innovation will be determined by relative profits. When $\pi > 1$ innovators will concentrate on energy-complementing research activities and N increases, while when $\pi < 1$ labour-complementing activities are more profitable, and N decreases. The expression above shows that the entrepreneurs' choice of the sector to invest in is determined by the relative price of the intermediate goods (the *price effect*) and by the relative amount of factors to which a machine type is complementary (the *market-size effect*). In particular, for given technology, a decrease in energy supply leads to a reduction in relative profits through the market size effect and to an increase through the price effect, see (4.24). Which of the two effects prevails depends on the elasticity σ, as will be discussed later. In equilibrium, however, both types of innovation occur at the same time, leading to the no-arbitrage expression: $\pi = 1$.

Using this no-arbitrage relation, we can solve for the equilibrium level of the technology ratio, N:

$$N = (S^w)^{\sigma-1}. \tag{4.14}$$

As noted above, the effect of a decrease in energy supply on the direction of technical change, that is on whether N increases or decreases, depends on the size of σ. When labour- and energy-intensive goods are gross complements in final goods production ($\sigma < 1$), the price effect outweighs the market size effect and a decrease in energy supply induces an increase in the range of energy complementary machines. However, when $\sigma > 1$ the result is reversed, and the reduction in energy supply induces an increase in the range of labour-complementary machines.

Substituting the expression for the equilibrium value of N in (4.12) and (4.13) provides the key expressions for the equilibrium allocation of labour under directed technical change:

$$\phi^{1/(\sigma-2)} L_E^{(\phi(\sigma-1)-1)/(\sigma-2)} + L_E = \overline{L}, \tag{4.15}$$

for the case when both countries are symmetric, and

$$\phi^{1/(\sigma-2)} \left[\left(L_E^c\right)^{\phi} \left(L_E^u\right)^{(\phi-1)/(\sigma-2)} + \left(L_E^u\right)^{(\phi(\sigma-1)-1)/(\sigma-2)} \right] + L_E^c + L_E^u = 2\overline{L}, \tag{4.16}$$

when country c faces a binding ceiling on its CO_2 emissions.

Thus, (4.12) and (4.13) summarize the long-run equilibrium of our model with and without unilateral climate policy under undirected technical change, while the last two equations do the same for the case of directed technical change.

4.3 Unilateral climate policy and carbon leakage

We now turn to the analysis of the effects of unilateral climate policy, in terms of carbon leakage, across different regimes of technical change. To compare different scenarios, we need to start from a common baseline. The natural baseline to choose is the long-run equilibrium of the model with directed technical change when both countries are unconstrained, equation (4.12). This baseline is characterized by the (symmetric) equilibrium level of labour devoted to energy generation L_E and by the corresponding (endogenous) technology ratio N. In order to have comparable baselines across technology regimes, we need to choose γ, the probability for an innovator to end up with an energy-complementing blueprint, such that $\gamma/(1-\gamma) = N$ equals the level prevailing under directed technical change (see Section 4.1).

Starting from this common equilibrium, we introduce an emissions constraint in one of the countries and study the degree of carbon leakage that occurs along the balanced growth path. We first study carbon leakage when technical change is undirected. Then we move on to the model with directed technical change and discuss how and why the results from this model differ from the model with 'traditional' endogenous growth.

4.3.1 Carbon Leakage under undirected technical change

Carbon leakage occurs when the unconstrained region increases its emissions in reaction to a reduction in emissions by the other country (i.e. when $L_E^u > L_E$). Intuitively it would seem clear that there should always be some carbon leakage: when a country exogenously reduces its supply of energy by introducing a limit to the amount of emissions, the energy intensive good becomes scarcer on its domestic market, giving rise to an increase in its relative price. This creates some scope for trade: the unconstrained economy now enjoys a comparative advantage in the production of the dirty good and will expand its production thereof. As a consequence L_E^u and hence emissions Z^u increase. We call this the *terms-of-trade effect* of a unilateral emission constraint. This result indeed holds in the case of undirected technical change, as formalized by the following proposition.

Proposition 4.1. *When technical change is undirected, carbon leakage will always be positive along the balanced growth path.*

Proof. Take the ratio of (4.12) and (4.13) and rearrange to find:

$$\left(\frac{L_E^{\phi}}{\left(L_E^u\right)^{\phi}+\left(L_E^c\right)^{\phi}}\right)^{-1/\sigma}\left(\frac{2\overline{L}-L_E^c-L_E^u}{\overline{L}-L_E}\right)^{-1/\sigma}=\left(\frac{L_E}{L_E^u}\right)^{1-\phi}.$$

Assume that $L_E^u \leq L_E$. Then the right hand side is larger than or equal to one while the left hand side is smaller than one. So we have a contradiction, hence $L_E^u > L_E$. □

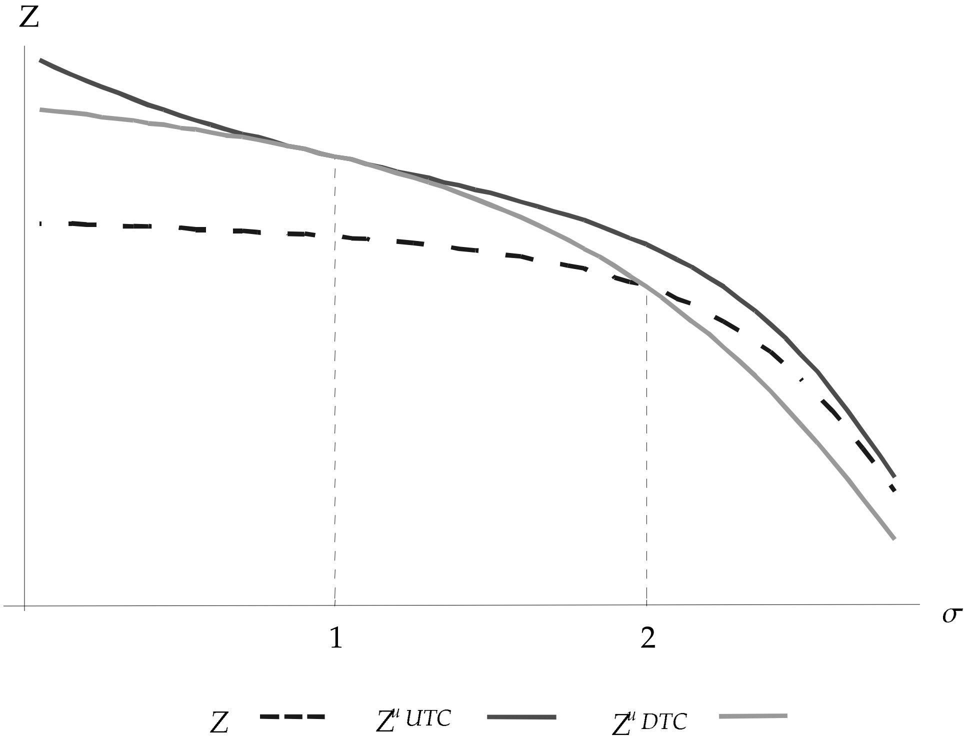

Figure 4.1: *Emissions in the unconstrained model (Z), in the constrained model under undirected technical change ($Z^u UTC$), and under directed technical change ($Z^u DTC$)*

We illustrate this result in Figure 4.1, where the dark dashed line represents emissions (or equivalently energy production) in each country when both are unconstrained. The amount of emissions by the unconstrained country when the other country faces a binding emission constraint, under undirected technical change is represented by the solid black line.[36] The figure clearly shows that emissions in the unconstrained region always increase following the introduction of the cap. In addition, we see that the amount of energy produced in the unconstrained region is declining with σ, the elasticity of relative demand for energy with respect to its relative price. The higher this elasticity, the lower the demand for energy in the constrained economy following the imposition of the constraint, hence the lower the export-led increase in energy generation.

When technical change is endogenous but undirected, unilateral climate policy is

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[36] The figures in this chapter are obtained from numerical simulations, using as baseline parameters values: $\overline{L} = 1$, $\phi = 0.4$, and $\sigma \in (0, 3.5)$. For each value of σ the corresponding value for N for the model with directed technical change were computed and the appropriate γ calibrated such that both models start from the same baseline. For the sake of graphical clarity, the graphs are plotted over a smaller range for σ.

undermined by emission increases by unconstrained countries. However, it seems intuitively clear that changes in relative prices *cœteris paribus* will not lead to an increase in global emissions. Climate policy will shift production to the unconstrained country (Proposition 4.1), but the increase in the relative price of the carbon intensive good will at the same time lead to a reduction in global energy demand. To address this formally, we look at the impact of a change in the level of the cap on total emissions, $\left[\left(L_E^c\right)^\phi + \left(L_E^u\right)^\phi\right]$, and derive the following result:

Proposition 4.2. *When technical change is undirected, global emissions will always decrease following a tightening of the emission constraint.*

Proof. By total differentiation of (4.13), we get:

$$\frac{\mathrm{d}L_E^u}{\mathrm{d}L_E^c} = -\frac{A(L_E^u)^{\sigma(1-\phi)}\phi(L_E^c)^{\phi-1}+1}{A(L_E^u)^{\sigma(1-\phi)}\left\{\phi(L_E^u)^{\phi-1}+\sigma(1-\phi)\left[(L_E^c)^\phi+(L_E^u)^\phi\right](L_E^u)^{-1}\right\}+1}, \tag{4.17}$$

where $A \equiv \phi^{-\sigma}N^{1-\sigma}$. Let $E^w \equiv \left[\left(L_E^c\right)^\phi + \left(L_E^u\right)^\phi\right]$ be total emissions. Thus, E^w decreases with a tightening of the cap whenever $\mathrm{d}E^w/\mathrm{d}L_E^c > 0$. Differentiating E^w, and rearranging terms shows that $\mathrm{d}E^w/\mathrm{d}L_E^c > 0$ requires:

$$\frac{\mathrm{d}L_E^u}{\mathrm{d}L_E^c} > -\frac{(L_E^c)^{\phi-1}}{(L_E^u)^{\phi-1}}.$$

This and (4.17) in turn imply that total emissions decline whenever

$$\frac{A(L_E^u)^{\sigma(1-\phi)}\phi(L_E^c)^{\phi-1}+1}{A(L_E^u)^{\sigma(1-\phi)}\left\{\phi(L_E^u)^{\phi-1}+\sigma(1-\phi)\left[(L_E^c)^\phi+(L_E^u)^\phi\right](L_E^u)^{-1}\right\}+1} < \frac{(L_E^c)^{\phi-1}}{(L_E^u)^{\phi-1}}.$$

Straightforward calculations show this to be equivalent to:

$$-A(L_E^u)^{\sigma(1-\phi)}\left[(L_E^c)^\phi+(L_E^u)^\phi\right](L_E^u)^{-1}-(L_E^c)^{\phi-1}+(L_E^u)^{\phi-1}<0.$$

Since $L_E^c < L_E^u$ and $\phi \in (0,1)$, the above inequality is always true. □

To illustrate this result, we present the leakage rate, the ratio of the induced increase in emissions in the unconstrained country and the emission reduction in the constrained region, i.e. $\left[(L_E^u)^\phi-(L_E)^\phi\right]\Big/\left[(L_E)^\phi-\left(L_E^c\right)^\phi\right]$, as a function of σ in Figure 4.2. The leakage rate for the case of undirected technical change is represented by the dark line. As the figure shows, the leakage rate is always positive, but less than 1.

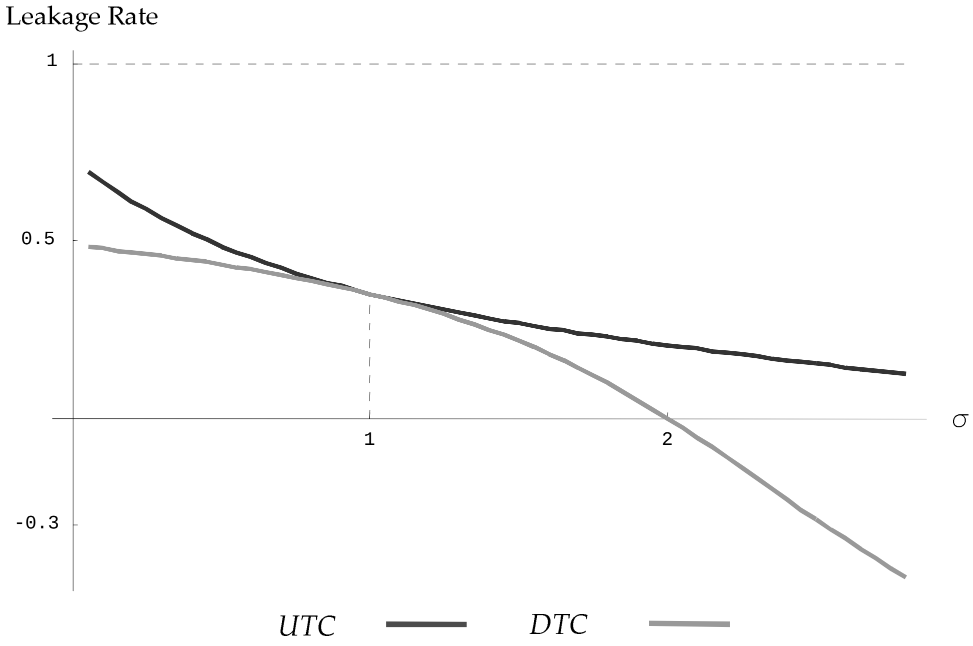

Figure 4.2: *Leakage rate under undirected (UTC) and directed (DTC) technical change*

4.3.2 Carbon leakage under directed technical change

In this section we focus on the central point of our analysis and derive our main results comparing the effects of an emission cap across regimes of technical change. We start by noting that allowing for directed technical change effectively provides the economy with an additional instrument to cope with the consequences of the introduction of a binding cap in the constrained country. Changes in the composition of technology may enable the unconstrained country to meet the increased demand for energy intensive goods while diverting less labour from its relatively more productive use in the Y_L sector. This is what we call the *induced-technology effect* of a unilateral emission constraint. We will show that this effect has the opposite sign to the terms-of-trade effect introduced above and hence tends to reduce carbon leakage.

We can compare the two versions of the model using the Le Chatelier principle (see e.g. Silberberg, 1990). Taking the total differential of (4.13) and rearranging we can write the total effect of a change in the cap on emissions in the unconstrained country as:

$$\left.\frac{\partial L_E^u}{\partial L_E^c}\right|_{DTC} = \left.\frac{\partial L_E^u}{\partial L_E^c}\right|_{UTC} + \frac{\partial L_E^u}{\partial N}\frac{\mathrm{d}N}{\mathrm{d}L_E^c}, \tag{4.18}$$

where DTC indicates directed technical change and UTC undirected technical change. We can interpret this expression as saying that the overall effect of the cap when allowing for directed technical change (the left hand side) can be decomposed in a *terms-of-trade effect*, represented by the first term at the right-hand side, and an *induced-technology effect*. Whether these two effects act in the same direction or not ultimately determines under which regime we can expect leakage to be higher. In order to draw any conclusion, we need to sign the components of the above equation, thus getting the following result:

Proposition 4.3. *For $\sigma \neq 1$ carbon leakage will be smaller with directed technical change than with undirected technical change. For $\sigma = 1$ it will be identical across regimes.*

Proof. From Proposition 4.1 we know that $\partial L_E^u / \partial L_E^c \big|_{UTC} < 0$.
As for $\partial L_E^u / \partial N \cdot \mathrm{d}N / \mathrm{d}L_E^c$, consider first the case where $\sigma < 1$. From (4.14), it is immediate that $\mathrm{d}N/\mathrm{d}L_E^c < 0$. Moreover, from (4.13), when N (and hence $N^{1-\sigma}$) increases, L_E^u must decline to satisfy the equation, *cœteris paribus*. Thus, $\partial L_E^u/\partial N < 0$. Hence $\partial L_E^u/\partial N \cdot \mathrm{d}N/\mathrm{d}L_E^c > 0$.
Consider now $\sigma > 1$. By symmetric arguments, $\mathrm{d}N/\mathrm{d}L_E^c > 0$ and $\partial L_E^u/\partial N > 0$, implying once more $\partial L_E^u/\partial N \cdot \mathrm{d}N/\mathrm{d}L_E^c > 0$.
Finally, consider $\sigma = 1$. In this case N equals 1, irrespective of the value of S^w, hence $\mathrm{d}N/\mathrm{d}L_E^c = 0$. □

This result shows that the induced-technology effect works against the standard terms-of-trade effect of Proposition 4.1. It thus lowers the amount of carbon leakage that would occur if technical change were not directed. Figure 4.1 shows the two effects. The pure terms-of-trade effect can be read from the upwards shift of emissions from the dashed dark line (the model without a cap) to the dark solid line (the model with a cap and undirected technical change). The induced technology effect is summarized by the move from the solid black line to the light gray one (the model with a cap and directed technical change). Indeed, the amount of emissions is lower when technical change is directed, with the exception of the case where $\sigma = 1$. This is due to the fact that when $\sigma = 1$ our CES specification in (4.1) reduces to a Cobb-Douglas production function, in which case technical change will always be neutral to the inputs concerned.[37]

The key mechanism at work here, is that the type of technical change induced by the emission constraint proves to be always energy-saving. To show this, we first analyze how the composition of technology is affected by the introduction of the cap. Successively we address the interaction between changes in N and the level of

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[37] Notice that, formally, we would need share parameters summing up to one in (4.1) to obtain a constant-returns-to-scale Cobb-Douglas production function as ε (and hence σ) goes to 1.

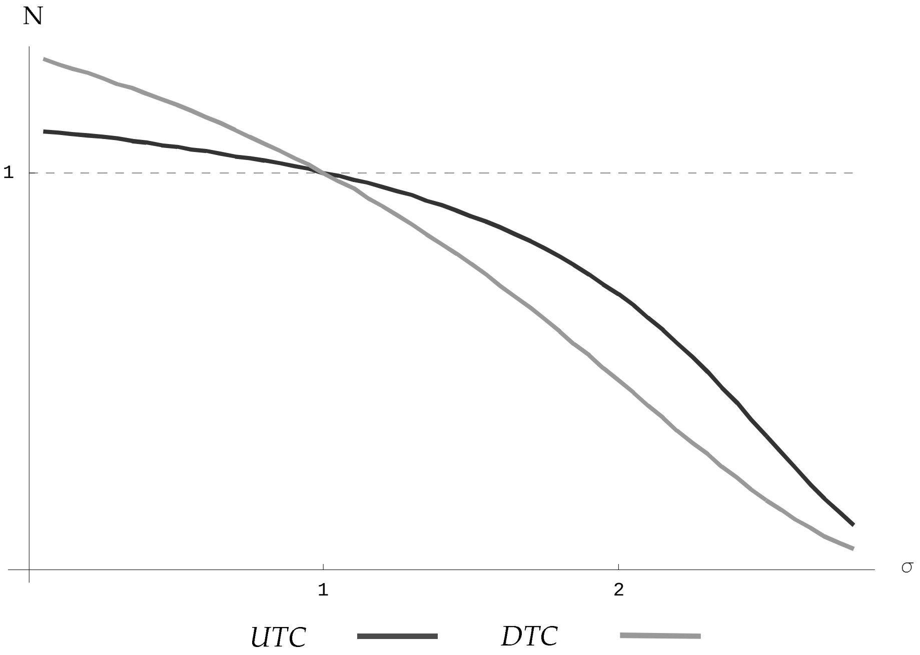

Figure 4.3: *Technology ratios (N) under undirected and directed technical change*

σ, to explain the impact of technical change on the evolution of the relative factor shares in our economy.

The composition of technology evolves according to the relative profitability of R&D in the different sectors. As noted in section 4.2, the final effect of introducing a cap (i.e. a change in S^w) on relative profits depends both on changes in the relative market size and in relative prices. Climate policy reduces the amount of energy produced, and hence decreases the potential size of the market for new energy-complementing innovations. At the same time, it makes energy scarcer, thereby rising the price of energy and making an innovation for the energy intensive good more valuable. Whether the negative market size effect or the positive price effect dominates depends on σ, the elasticity of the relative demand for energy with respect to its relative price. Since in the long-run equilibrium the technology ratio is given by (4.14), we see that whenever $\sigma < 1$ the price effect dominates and the introduction of a cap induces an increase in N. When $\sigma > 1$ on the other hand, the market size effect dominates and N decreases. This relation between N and σ is plotted in Figure 4.3, where the dark line represents the ratio of technology under undirected technical change, while the lighter one depicts the case of directed technical change.

Recalling the expression for relative factor productivity from (4.11), we can write the relative value share of energy to labour in country u as,

$$\frac{w_E E^u}{w_L L_L^u} \equiv wS^u = N^{(\sigma-1)/\sigma}(S^w)^{-1/\sigma}S^u.$$

We see that, for given N, the effect of the introduction of the cap (a decrease in S^w) is to unambiguously increase the share of energy in the unconstrained country. We know from the result in Proposition 4.1 that, when N is constant, leakage is always positive. Once we allow N to change in response to economic incentives, however, some form of induced energy-saving technical change occurs. The expression above shows how the effect of a change in the technology ratio on relative factor shares depends on σ. As discussed above, when $\sigma < 1$, N is higher than in the case of undirected technical change (see Figure 4.3). Thus, $N^{(\sigma-1)/\sigma}$ is lower, and the increase in the energy share due to the cap is counteracted by the induced change in technology. The same is true when $\sigma > 1$. In this case, however, both N and $N^{(\sigma-1)/\sigma}$ are below their baseline levels. Thus, irrespective of the level of σ, the effect of the induced change in technology ($N^{(\sigma-1)/\sigma}$) is to mitigate the terms-of-trade effect (which works through $(S^w)^{-1/\sigma}$). We can conclude that the technical change induced by the introduction of unilateral climate policy reduces the share of energy. Thus, technical change is endogenously energy-saving in our model. As shown in Proposition 4.3, directed technical change unambiguously leads to lower rates of carbon leakage.

The last question we want to address is whether the induced-technology effect we just highlighted can more than offset the terms-of-trade effect, and lead to a situation where carbon leakage is negative. Figure 4.1 shows that an affirmative answer is in order. Indeed, the curve representing emissions under directed technical change (the light curve) dips below the graph of the baseline case (the dashed curve), as σ gets larger. The following proposition makes it formal using a log-linearized version of our model, derived in Appendix 4.B:[38]

Proposition 4.4. *When technical change is directed, carbon leakage due to a marginal tightening of the emission constraint will be positive for $\sigma < 2$, zero for $\sigma = 2$, and negative for $\sigma > 2$.*

Proof. In section 4.B.2 of the Appendix we use a log-linearized version of the model to show that, around the equilibrium, we may write:

$$\frac{\widetilde{L_E^u}}{\widetilde{L_E^c}} = \frac{(\sigma-2)\left(\left(1-\eta\right)\phi + \chi\frac{L_E^c}{L_E^u}\right)}{(2-\sigma)\left(\eta\phi+\chi\right)+1-\phi}. \tag{4.19}$$

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[38] Although this proposition represents a local result, all our simulations confirm this pattern for the model in levels.

As discussed in Appendix 4.B, a necessary condition for a stable equilibrium is that the term at the denominator be positive. Moreover, the second term in parenthesis at the numerator is always positive. Hence, around a stable equilibrium, we have $\widetilde{L_E^u}/\widetilde{L_E^c} \gtreqless 0$ whenever $\sigma \gtreqless 2$. □

This proposition shows that, when technical change is directed, the induced-technology effect can outweigh the terms-of-trade effect, provided that the elasticity of the relative demand for carbon-based energy is 'sufficiently large'. Whether σ larger than two is a plausible case, however, is difficult to assess from the available literature. In our model energy, E, implicitly stands for energy generated from fossil fuels rather than energy *tout-court*, as its generation directly causes the emissions of carbon dioxide. Where long-run own-price elasticities for 'broad' energy are estimated in the range 0.2 to 1.76 (see e.g. Pindyck and Rotemberg, 1983, Popp, 2001, Gately and Huntington, 2002), the estimates for fossil fuel products have values of up to 2.72 (see e.g. Bates and Moore, 1992, Espey, 1998, Taheri and Stevenson, 2002). Since σ can be interpreted as the price elasticity for *aggregated* fossil fuels, the former estimates may provide a lower bound for σ while the latter may be seen as an upper bound. In this respect, a long-run value for the demand elasticity of fossil fuels of around 2 does not seem implausible.

4.4 Discussion and conclusions

The refusal of the United States to ratify the Kyoto Protocol is seen by many as a serious threat to the Protocol's effectiveness. If a coalition of technologically advanced (and hence fossil-fuel dependent) economies decides to voluntarily reduce its emissions of carbon dioxide, this will increase the price of dirty goods within this coalition. Unconstrained countries, such as the US, might benefit from increasing their production of dirty goods and exporting them to coalition members, thereby offsetting the decrease in emissions by the ratifying countries (carbon leakage).

However, environmental policy affects relative prices, and hence it modifies the relative profitability of inventing for the clean or dirty goods industry. The effects of changes in the direction of technical change on carbon leakage cannot be ignored. In this chapter we studied these effects taking explicitly into account that a technologically advanced country is outside the coalition. We presented a stylized theoretical model, which compares the results of a scenario where technology in the clean and dirty sectors is allowed to develop differently (directed technical change), to those derived from a model of 'traditional' endogenous technical change. We have shown that taking into account the endogeneity of the direction of technical change always leads to lower leakage rates than when this induced technology effect is ignored. We have also discussed the possibility that the sign of carbon leakage be reversed. When the elasticity of demand for carbon-based energy is sufficiently high, the change in technology due to the emission constraint is such that it becomes optimal for the unconstrained country to cut back on its emissions.

In order to emphasize the role of technical change on carbon leakage as clearly as possible, we had to abstract from several other mechanisms that play a role in determining the degree of leakage. Clearly, preferences, endowments, and production possibilities all play a role in determining the global effect of unilateral climate policy. However, by abstracting from these aspects, we were able to highlight the effect of profit incentives on innovation and ultimately on carbon leakage. Comforted by the empirical literature (see footnote 28), we believe that our results highlight a general and relevant mechanism: energy-saving technical change in the presence of climate policy. Indeed, when technology is given, the global ratio of energy to other inputs decreases (see Proposition 4.2), a result that has been found in virtually all of the CGE literature. This, in turn, induces energy-saving technological change, as we discussed in section 4.3.2. Relative to a situation without directed technical change, the global demand for carbon-based energy, the demand for fossil fuels in the unconstrained country, and hence the degree of carbon leakage, will all be lower.

Of course reality is more complicated than our stylized model. As mentioned in the introduction, there is at least one other important channel through which emissions leak from one country to the other. This we can broadly label the *energy-market channel*. When an emission cap is introduced, the price of carbon intensive fuels tends to decrease relative to cleaner ones, due to the decreased demand by constrained countries. As dirtier inputs become cheaper, countries outside the climate agreement tend to increase their demand, leading to additional carbon leakage.[39] The strength of this mechanism depends on the ease of inter-fuel substitution (whether it is technically possible to substitute natural gas for coal, for example), on the elasticity of supply of the different fuels, and on the possibility of trading different types of fuel internationally. The technical possibility to substitute one fuel for the other affects the size of the shift in demand following a change in the relative price. On the other hand, changes in relative prices also depend crucially on the decision of fuels producers whether to reduce supply as the price falls, and to what extent. Finally, if fuels (or some of them) are not easily traded internationally, the scope for substitution (and for carbon leakage through this channel) might also be limited.

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[39] Given the differences in model assumptions for CGE models (see footnote 1), it is hard to say anything about the relative sizes of the energy market channel and the channel that works through trade in CO_2-intensive goods. According to Kuik (2005), CGE modelers seem to agree that the former channel is quantitatively the most important, at least in the short to medium term.

The sensitivity of carbon leakage rates to changes in the key elasticities determining substitution, supply responses and trading flows have been comprehensively analyzed by Burniaux and Oliveira Martins (2000). They conclude that the rate of leakage is higher, the higher the inter-fuel elasticity of substitution, the lower the elasticity of supply, and the higher the Armington elasticities among different fuels. Any of these elements could be the focus of possible extensions to our model. However, as long as the elasticities of supply are not too small (as seems reasonable, given the long-run perspective of our analysis), and as long as trade in coal is limited (which seems sensible, given that coal is a very bulky fuel which requires expansive infrastructures and entails high transport costs), the degree of carbon leakage will be lower than 100%. Recalling the discussion above on energy-saving technical change, this suggests that also in this more complex framework, the same mechanism would be preserved and carbon leakage would be lower when the direction of technical change is endogenous.

Our results lend some support to the position of those who advocate the Kyoto Protocol, and other forms of unilateral climate policy as effective means to reduce carbon emissions. We have shown that the leakage rates that inform the current debate might prove overestimated, since the available quantitative literature neglects the role of endogeneity in the direction of technical change. As a consequence, unilateral climate policy might be more effective than generally claimed. Moreover, we also hint at the (theoretical) possibility that, when the demand for carbon-based energy is sufficiently elastic, ratifiers' efforts could be compounded by emission *reductions* by unconstrained countries.

Finally, we should note that the quantitative impact of the mechanisms we have highlighted in this chapter depends on the key elasticities of the model. Thus, our theoretical conclusions need to be assessed through quantitative methods, first and foremost using CGE models that incorporate directed technical change. The calibration of such a model, however, would require reliable sector-specific data on technical progress. Building such a model, and finding the necessary data, constitutes a formidable challenge for future research.

4.A Appendix: Model solution

4.A.1 Undirected technical change

Profit maximization in the final good sector implies

$$\frac{Y_E^{dr}}{Y_L^{dr}} = \left(\frac{p_E}{p_L}\right)^{-\varepsilon}, \tag{4.20}$$

where p_j is the price of good Y_j, $j = E, L$. The superscript d indicates demand and avoid confusion with supply in (4.2) and (4.3).

Producers of the intermediate good Y_j maximize profits taking prices and technology as given. The first-order conditions for sector $j = E, L$ and country $r = c, u$ read:

$$k_j^r(i) = \left(\frac{p_j}{p_{k_j(i)}}\right)^{1/\beta} S_j^r, \text{ and} \tag{4.21}$$

$$w_j = \frac{\beta}{1-\beta} p_j \left(\int_0^{N_j} k_j^r(i)^{(1-\beta)} di\right)\left(S_j^r\right)^{\beta-1}; \tag{4.22}$$

where, $k_j^r(i)$ is the demand of machine of type i in sector j and country r, p_j is the price of good Y_j, and S_j is short-hand for primary inputs: $S_E = E$, and $S_L = L_L$.

Local licensees of blueprints act as monopolists. Assuming constant marginal costs equal to ω units of the final good, profit maximization implies $p_{k_j(i)} = \omega/(1-\beta)$. Letting $\omega = 1-\beta$, the price of machines in both sectors equals 1. As all machines are equally productive in production, and all entail the same cost, the demand of each machine will be the same, k_j say.

Using this, and substituting from (4.21) into (4.2) and (4.3), we obtain the following expression for the relative supply of intermediate goods:

$$Y^w = p^{(1-\beta)/\beta} S^w N; \tag{4.23}$$

where $N \equiv N_E/N_L$, $S^w \equiv (E^c + E^u) / \left(L_L^c + L_L^u\right)$, and $Y^w \equiv \left(Y_E^c + Y_E^u\right) / \left(Y_L^c + Y_L^u\right)$.

Equating (4.23) to (4.20) yields the market clearing relative price as

$$p = \left(NS^w\right)^{-\beta/\sigma}, \tag{4.24}$$

where $\sigma \equiv 1 + (\varepsilon - 1)\beta$.

Substituting (4.21) into (4.22), taking ratios and using (4.24), we get the relative factor rewards, for given technology (expression (4.11) in the main text):

$$w = N^{(\sigma-1)/\sigma}\left(S^w\right)^{-1/\sigma},$$

where $w \equiv w_E / w_L$.

Energy producers choose their labour input to maximize profits:

$$w = \frac{1}{\phi \left(L_E^r\right)^{\phi-1}}.$$

Equating this to the previous expression gives (implicitly) the equilibrium allocation of labour, for given N (expression (4.12) in the main text):

$$\phi^{-\sigma} N^{1-\sigma} L_E^{\phi(1-\sigma)+\sigma} + L_E = \overline{L}. \tag{4.25}$$

Under the cap, the amount of labour in energy production is determined as $L_E^c = (Z^c)^{1/\phi}$. Using this, and solving as before, gives the equilibrium allocation in the unconstrained country, for given N and L_E^c (expression (4.13) in the main text):

$$\phi^{-\sigma} N^{1-\sigma} \left[\left(L_E^c\right)^{\phi} \left(L_E^u\right)^{\sigma(1-\phi)} + \left(L_E^u\right)^{\phi(1-\sigma)+\sigma} \right] + L_E^c + L_E^u = 2\overline{L}. \tag{4.26}$$

4.A.2 Directed technical change

Potential innovators maximize the net present value of the stream of expected future profits. In standard dynamic programming equations:

$$r(t) V_j(t) - \dot{V}_j(t) = \pi_j(t),$$

where V_j is the value of an innovation in sector j and $r(t)$ is the interest rate at time t.

Along the balanced growth path (BGP) of the economy – i.e. a situation in which the prices are constant, and N_E and N_L grow at the same constant rate – profits do not change over time, so that $\dot{V}_j = 0$. Since entry is free in the R&D sector, the value of an innovation cannot exceed its cost, i.e. $V_j \leq 1/\nu$ in each sector. Moreover, along the BGP both types of innovation must occur at the same time, hence $V_j = 1/\nu$ in both sectors, leading to the no-arbitrage equation:

$$\pi_E \nu = \pi_L \nu, \text{ or } \pi_E / \pi_L = 1.$$

Using (4.21), the instantaneous profits of machine produces are:

$$\pi_E = \beta p_E^{1/\beta} E^w \quad \text{and} \quad \pi_L = \beta p_L^{1/\beta} L_L^w.$$

Plugging this into the no-arbitrage equation above, yields,

$$p^{1/\beta} S^w = 1.$$

Using (4.24), we solve this last expression for N, obtaining (expression (4.14) in the main text):

$$N = (S^w)^{\sigma-1}. \tag{4.27}$$

Substituting this into (4.25) yields the following expression for the equilibrium under DTC and in the absence of climate policy (expression (4.15) in the main text)

$$\phi^{1/(\sigma-2)} L_E^{(\phi(\sigma-1)-1)/(\sigma-2)} + L_E = \overline{L}.$$

Using (4.27) and (4.26), instead, provides the same expression for the case when country c imposes a ceiling to its CO_2 emissions (expression (4.16) in the main text).

$$\phi^{1/(\sigma-2)} \left[\left(L_E^c\right)^{\phi} \left(L_E^u\right)^{(\phi-1)/(\sigma-2)} + \left(L_E^u\right)^{(\phi(\sigma-1)-1)/(\sigma-2)} \right] + L_E^c + L_E^u = 2\overline{L}.$$

4.B Appendix: The log-linearized model

In this appendix we (log-)linearize the model around the steady state and derive several results.

4.B.1 Deriving the log-linearized model

The linearized version of the goods market equilibrium condition (4.13) reads:

$$(\sigma-1)\,\widetilde{N} = \left[\left(1-\phi\right)\sigma+\eta\phi+\chi\right]\widetilde{L_E^u} + \left[\left(1-\eta\right)\phi+\chi\frac{L_E^c}{L_E^u}\right]\widetilde{L_E^c}, \tag{4.28}$$

where a tilde, $\widetilde{\ }$, over a variable denotes a small percentage change, and where we have used the following definitions:

$$\eta \equiv \frac{\left(L_E^u\right)^{\phi}}{\left(L_E^u\right)^{\phi}+\left(L_E^c\right)^{\phi}} \in (0,1), \text{ and } \chi \equiv \frac{L_E^u}{2\overline{L}-L_E^c-L_E^u}. \tag{4.29}$$

The percentage changes in L_E^u and L_E^c denote any marginal change in the respective variable. For example, a decrease in L_E^c (that is a $\widetilde{L_E^c}<0$) from $L_E^c = L_E$ would represent the introduction of a marginal emissions cap in the country, while a decrease from any $L_E^c < L_E$ would represent any marginal tightening of an existing cap.

When we linearize the equilibrium condition for the market for innovations, (4.14), we find:

$$\widetilde{N} = (\sigma-1)\left(\left(1-\eta\right)\phi+\chi\frac{L_E^c}{L_E^u}\right)\widetilde{L_E^c} + (\sigma-1)\left(\eta\phi+\chi\right)\widetilde{L_E^u}. \tag{4.30}$$

4.B.2 Appendix to Proposition 4.4

To find (4.19), substitute (4.30) into (4.28) and rewrite to find:

$$\frac{\widetilde{L_E^u}}{\widetilde{L_E^c}} = \frac{(\sigma-2)\left(\left(1-\eta\right)\phi+\chi\frac{L_E^c}{L_E^u}\right)}{(2-\sigma)\left(\eta\phi+\chi\right)+1-\phi}. \tag{4.31}$$

The denominator of this expression will be positive around any stable equilibrium. Indeed, the dynamics of the system require that at any stable equilibrium the slope of the goods market equilibrium condition be steeper than the R&D equilibrium condition in the (L_E, N) space. The relevant slopes can be easily derived from (4.28) and (4.30). For $\sigma < 1$ the stability condition discussed above requires:

$$\left.\frac{\widetilde{N}}{\widetilde{L_E^u}}\right|_{GME} = \frac{(1-\phi)\sigma+\eta\phi+\chi}{\sigma-1} < \left.\frac{\widetilde{N}}{\widetilde{L_E^u}}\right|_{R\&DE} = (\sigma-1)(\eta\phi+\chi),$$

where the subscripts GME and $R\&DE$ indicate the goods markets and the R&D market equilibrium conditions, respectively. The sign of the inequality is reversed for the case when $\sigma > 1$. Since in both cases one can easily verify that the stability condition simplifies to

$$(2-\sigma)\left(\eta\phi+\chi\right)+1-\phi>0,$$

we have established our claim.

4.C Appendix: Existence and stability of the equilibrium

The general equilibrium of the model requires that equilibrium on the goods market (18) and equilibrium on the market for innovations (21) are satisfied at the same time. Rearranging these expressions we get for the goods' market equilibrium:

$$N = \left(\frac{(\overline{L} - L_E)\phi^{\sigma}}{L_E^{\sigma(1-\phi)+\phi}} \right)^{\frac{1}{1-\sigma}}. \tag{GME}$$

and for the no-arbitrage equation in innovation:

$$N = \left(\frac{L_E^{\phi}}{\overline{L} - L_E} \right)^{\sigma-1}; \tag{TECH}$$

We have the following result:

Proposition 4.5. *For all $\sigma \in \left(0, \frac{1+\phi}{\phi}\right)$ there exists a unique stable (interior) equilibrium. When $\sigma > \frac{1+\phi}{\phi}$, the stable equilibrium collapses to the corner where $L_E = 0$.*

Sketch of proof: We proceed to prove the proposition resorting to a graphical analysis, interpreting TECH and GME as lines in the (L_E, N) plane. We distinguish four different cases:

i. $\sigma \in (0,1)$. In this case both TECH and GME are downward sloping, and both have a vertical asymptote at $L_E = 0$ (See Figure 4.4). Moreover, both cross the horizontal axis at $L_E = \overline{L}$. Since the limit of the ratio of TECH/GME as $L_E \to 0$, goes to 0, it is clear that GME is above TECH in a neighbourhood of $L_E = 0$. Analyzing the slope of both curves at $L_E \to \overline{L}$ reveals that, since the slope of TECH$\to \infty$ while GME's tends to 0, TECH is above GME as L_E approaches its maximum value ($\overline{L}$). This is enough to prove that there is at least one point of interception such that $L_E \in (0, \overline{L})$. Moreover, since GME is strictly convex while TECH is convex-concave with one inflection point, it follows that this equilibrium is unique.

   Let us now consider the dynamics of the system outside the equilibrium. From the ratio of profits in the two sectors,

$$\pi = N^{-\frac{1}{\sigma}} S^{\frac{\sigma-1}{\sigma}},$$

   we see that when $\sigma < 1$ an increase in L_E above the level that satisfies the no -arbitrage condition $\pi = 1$ (that is, a point to the right of TECH), the relative

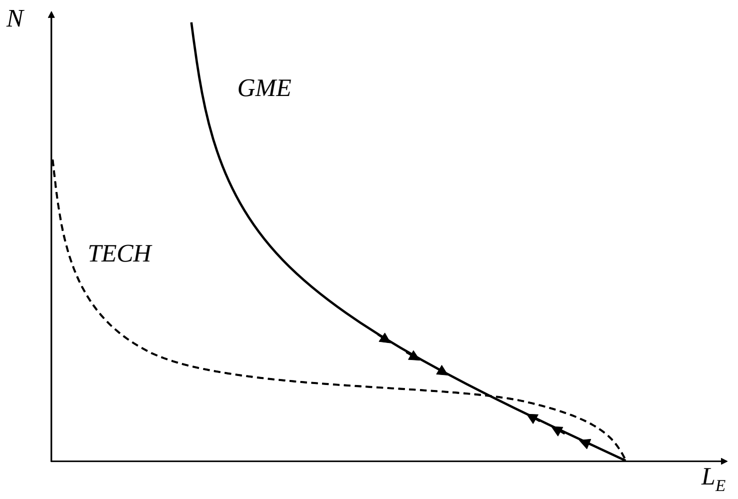

Figure 4.4: *Stable Equilibrium when* $\sigma < 1$

profitability of innovation in the energy sector decreases. The subsequent adjustment requires an increase in innovation effort (and thus in the number of blueprints) in the labour-intensive sector, that is a decrease in N. The opposite is true for a decrease in the amount of labour employed in the energy sector.

Since the composition of labour across sectors adjusts immediately, the dynamics of the system will be such that it will always move along the GME locus. As the graphical illustration in Figure 4.4 makes clear, an equilibrium will be stable only if there GME is steeper that TECH. In the case depicted in the picture, the only stable equilibrium will be the interior one, since at the corner solution where $L_E = \overline{L}$ the TECH curve is steeper than the curve of GME.

ii. $\sigma \in (1,2]$. The analysis of this case is specular to the one above. In this case both curves are upward sloping and both have an asymptote at $L_E = \overline{L}$. Analyzing the relative positions and the curvatures, we can conclude once again that only one stable equilibrium exists and it is the interior one. The corner equilibrium at $L_E = 0$ is unstable.

iii. $\sigma \in \left(2, \frac{1+\phi}{\phi}\right)$. As in the previous case, both curves are upward sloping. However, the curvatures of the two curves change with σ, and when $\sigma > 2$ GME falls below TECH in the neighbourhood of $\overline{L}$ so that the previous argument does not hold anymore. In order to prove that an equilibrium still exists we focus on a marginal change in σ, starting from $\sigma = 2$, for which case we know that an interior stable equilibrium exists at $L_E = \phi^{1/1-\phi}$. Simple comparative statics tell us that GME pivots clockwise around a point whose abscissa is $L_E = \frac{\phi}{1+\phi}\overline{L}$, whereas TECH pivots counter-clockwise around a point further to the right. Since $L_E = \frac{\phi}{1+\phi}\overline{L}$ is necessarily to the right of $L_E = \phi^{1/(1-\phi)}$ for $\overline{L} \geq 1$, it follows that the two curves will move in opposite directions, and they will cross even after the marginal change. The equilibrium point will shift to the left and towards the origin. We can iterate this argument as long as the curvatures are stable, tracing the stable equilibrium in its approach to the origin. When σ reaches the boundary point $\frac{1+\phi}{\phi}$, the interior equilibrium collapses to the origin which becomes the only stable equilibrium.

Since TECH is above GME around $L_E = 0$ and $L_E = \overline{L}$, and since we have just proved that they cross at least once, this implies that they will actually cross twice. Another equilibrium point indeed exists, but it can be shown to be unstable as there GME is flatter than TECH.

iv. $\sigma \in \left(\frac{1+\phi}{\phi}, +\infty\right)$. In this (degenerate) case the two curves only cross at the origin of the axes, thus the only equilibrium obtains where $L_E = 0$. As this case is not interesting for our analysis, we restrict our attention to the case where $\sigma \in \left(0, \frac{1+\phi}{\phi}\right)$.

This concludes our sketch of the proof.

CHAPTER 5

Production functions for climate policy modeling: an empirical analysis[40]

The recent literature on the long run effects of climate policy focusses on the alleviating effect of endogenous technological change on the costs of climate policy. That is, it studies the welfare gains from research and development or from learning-by-doing effects when the economy faces some form of climate policy, compared to a scenario without endogenous technological change. Next to investing in new technologies, applied climate policy models allow firms to react to price changes, caused by climate policy, through input substitution, e.g. shifting away from energy towards capital or labour. Since the endogenous changes in technology are themselves determined by the price changes and the substitution possibilities – the easier it is to substitute away from energy, the smaller may be the need to invest in energy-saving technologies –, it is important that the substitution possibilities in applied climate policy models are not only empirically founded, but also disentangled from changes in the production isoquant that come from technological change: too high or too low elasticities may lead to under- or overestimates of the effects of endogenous technological change. In addition, the results of simulations without technological change are sensitive to the elasticity of substitution. Indeed, Jacoby et al. (2006) found that, in the MIT EPPA model, the elasticity of substitution between energy and value-added (the capital-labour composite) is the parameter that affects the costs of ”Kyoto forever” for the U.S. economy the

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[40] This chapter is a slightly adjusted reprint of Van der Werf (2008). I am grateful to Daan van Soest and Sjak Smulders for their help and useful discussions. In addition I thank Katie Carman, Anne Gielen and Johannes Voget for discussions and comments.

most.

Unfortunately, in most applied dynamic climate policy models, neither the production structure nor the accompanying elasticities of substitution have an empirical basis. The current chapter therefore estimates production functions for climate policy models. We study all possible nesting structures for the constant elasticity of substitution (CES) production function, while taking into account that both substitution possibilities and technological change affect the production possibilities frontier.

In applied climate policy models the ease with which one can substitute one input for another is generally represented by elasticities of substitution. As they generally use CES production functions with capital, labour and energy as inputs, applied climate models can choose between different structures for the production function. For example, capital and energy can be combined first using a two-input CES function with a specific elasticity of substitution, and subsequently this composite can be 'nested' into another CES function, where it is combined with labour (with possibly a different elasticity).

Table 5.1 presents an overview of the production structures, elasticities of substitution and types of technological change of some dynamic models that simulate the effect of climate policy on the economy. The table shows that the nesting structure differs between the various papers. Moreover, 3 out of 10 models do not nest at all and treat all inputs at the same level. A second observation is that in all models but one, capital is in the same nest as labour. One could nevertheless argue that capital and energy should be combined first, as is done in the GREEN model (Burniaux et al., 1992), since (physical) capital and energy generally operate jointly.

When we look at the elasticities of substitution in Table 5.1, we see that models use different values for the elasticities of substitution, even when they use the same nesting structure. In addition, many models use the knife-edge case of a unit elasticity and hence neutral technological change in (part of) the production function. When the elasticity of substitution is equal to one, the CES function reduces to a Cobb-Douglas function, in which case relative factor productivity is unaffected by technological change. Hence the choice for a unit elasticity greatly affects the role of technological change in model simulations.

The way in which technological change enters the production function differs as well (we define technological change as a change in the position or shape of the production isoquant, for a given elasticity of substitution). Focussing on endogenous technological change, we see that four of the models in Table 5.1 use energy specific technological change, two models use total factor productivity (TFP) growth (both at the industry level), and only one model uses factor-specific technological change.

Table 5.1: Nesting structure and elasticities of substitution for several models

Author(s)	Nesting structure[a]	Elasticities[b]	Techn. change[c]
Bosetti et al. (2006)	(KL)E	$\sigma_{K,L} = 1$; $\sigma_{KL,E} = 0.5$	exog. TFP; endog. energy-specific
Burniaux et al. (1992)[d]	(KE)L	$\sigma_{K,E} = 0$ or 0.8; $\sigma_{KE,L} = 0$ or 0.12 or 1	exogenous
Edenhofer et al. (2005)	KLE	$\sigma_{K,L,E} = 0.4$	endog. factor-specific
Gerlagh and Van der Zwaan (2003)	(KL)E	$\sigma_{K,L} = 1$; $\sigma_{KL,E} = 0.4$	endog. energy-specific
Goulder and Schneider (1999)	KLEM	$\sigma_{K,L,E,M} = 1$	endog. TFP
Kemfert (2002)	(KLM)E	$\sigma_{KLM,E} = 0.5$	endog. energy-specific
Manne et al. (1995)	(KL)E	$\sigma_{K,L} = 1$; $\sigma_{KL,E} = 0.4$	exogenous
Paltsev et al. (2005)	(KL)E	$\sigma_{K,L} = 1$; $\sigma_{KL,E} = 0.4 - 0.5$	exogenous
Popp (2004)	KLE	$\sigma_{K,L,E} = 1$	endog. energy-specific
Sue Wing (2003)[e]	(KL)(EM)	$\sigma_{K,L} = 0.68 - 0.94$; $\sigma_{E,M} = 0.7$; $\sigma_{KL,EM} = 0.7$	endog. TFP

[a] (KL)E means a nesting structure in which capital and labour are combined first, and then this composite is combined with energy with a different elasticity of substitution. KLE means that all inputs are in a single-level CES function.

[b] $\sigma_{i,j}$ is the elasticity of substitution between inputs i and j and $\sigma_{ij,k}$ is the elasticity of substitution between the composite of inputs i and j on the one hand, and input k on the other.

[c] TFP = Total Factor Productivity growth.

[d] Lower elasticities for old capital, higher elasticities for new capital.

[e] Elasticities taken from Cruz and Goulder (1992).

In sum, dynamic climate policy models differ along three dimensions: nesting structure, the sizes of the elasticities, and the way in which technological change affects marginal productivities. Surprisingly, the production functions used by the models in Table 5.1 generally lack empirical foundation. While authors refer to other papers – that don't have empirical validations themselves – for the nesting structures and elasticities chosen, technology is generally modeled in a way that the modeler suits best, or to best answer the question under scrutiny. The current chapter offers an empirical analysis of all three dimensions by estimating CES production functions for all possible nesting structures. Accordingly, we report the accompanying elasticities of substitution for each nesting structure and conclude which nesting structure fits the data best.

We find that the (KL)E nesting structure, that is a nesting structure in which capital and labour are combined first, fits the data best, but we generally cannot reject that the production function has all inputs in one CES function (i.e. a 3-input 1-level CES function). These nesting structures are used by most of the models in Table 5.1. However, for the (KL)E nesting structure we reject that elasticities are equal to 1, in favour of considerably lower values, whereas several of the climate policy models in the table use a Cobb-Douglas function for (part of the) production function. Finally we estimate (constant) rates of factor-specific technological change, and test for different technology trends. We reject the hypothesis that only energy-specific technological change matters, and the hypothesis of total factor productivity (TFP) growth, in favour of factor-specific technological change. That is, technology trends differ significantly between capital, labour and energy.

In all models in Table 5.1, firms minimize costs. Hence estimates of constant substitution elasticities for dynamic climate policy models should start from firms' optimizing behavior. Only a few papers have estimated CES production functions with capital, labour and energy as inputs, using equations that are derived from optimizing behavior by firms. Prywes (1986) and Chang (1994) both use ratios of first-order conditions to estimate the parameters of a (KE)L nesting structure, disregarding the (KL)E and (LE)K structures.[41] Both authors first use the ratio of the first-order conditions for capital and energy to estimate the elasticity of substitution between capital and energy, which we denote by $\sigma_{K,E}$. Using this estimate, they derive fitted values for composite input Z and its price P_Z, which are subsequently employed to estimate the elasticity of substitution between the capital-energy composite on the one hand and labour on the other, which we denote by $\sigma_{KE,L}$. For this they exploit the first-order conditions with respect to labour and Z. However, when taking ratios of first-order conditions, it becomes impossible to identify the individual technology parameters, which we need to study how tech-

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[41] In a footnote, Chang (1994) claims he compared several nesting structures and chose to combine capital and energy first, based on the R^2. However, he does not report his results.

nological change affects the production function.[42]

Prywes (1986) uses pooled data from 4-digit U.S. industries for the period 1971-1976 to estimate elasticities for 2-digit industries. He finds estimates for $\sigma_{K,E}$ ranging from -0.57 to 0.47. His estimates for $\sigma_{KE,L}$ range from 0.21 to 1.58. Chang (1994) uses time series data for Taiwan and finds the elasticity of substitution between capital and energy to be about 0.87, and the one for labour and the capital-energy nest to be around 0.45.

The remainder of the chapter is organized as follows. We first introduce the nested CES production function and derive the equations to be estimated. We then describe our dataset and the econometric method in section 5.2. In section 5.3 we present our estimation results, where we first discuss which nesting structure fits the data best and then present the estimated elasticities of substitution for each nesting structure. We explicitly test whether substitution elasticities differ significantly from one and whether the production function should be nested. Section 5.3.4 presents our results regarding technological change. In section 5.4 we confront our results with the production functions used in the literature on dynamic climate policy modeling. We summarize and conclude in section 5.5.

5.1 Model specification

The two-level three-input CES production function can be nested in three ways: (KL)E, (KE)L and (LE)K. For the purpose of illustration we focus in this section on the (KL)E structure, although we estimate all three nesting structures and present the results for all nesting structures in section 5.3. The (KL)E nesting structure looks as follows:[43]

$$Q = \left(\alpha (A_E E)^{\frac{\sigma_{KL,E}-1}{\sigma_{KL,E}}} + (1-\alpha)(Z)^{\frac{\sigma_{KL,E}-1}{\sigma_{KL,E}}} \right)^{\frac{\sigma_{KL,E}}{\sigma_{KL,E}-1}}, \tag{5.1}$$

with

$$Z = \left(\beta (A_K K)^{\frac{\sigma_{K,L}-1}{\sigma_{K,L}}} + (1-\beta)(A_L L)^{\frac{\sigma_{K,L}-1}{\sigma_{K,L}}} \right)^{\frac{\sigma_{K,L}}{\sigma_{K,L}-1}}. \tag{5.2}$$

When (5.2) is substituted into (5.1) we have a nested CES function where inputs capital K and labour L are combined to form a composite input Z in the lower

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[42] Prywes (1986) estimates total factor productivity growth separately from the first order conditions, using dummy variables. Hence his results on technological change do not affect his estimates of the substitution elasticities and are hence outside the scope of this chapter.

[43] As in the literature on general equilibrium climate policy modeling, we assume constant returns to scale production functions. Note that in models with endogenous technological change the returns to scale need not be constant at the aggregate level, although they are for each individual goods producer.

nest, which in turn is combined with the energy input E to give final output Q. In the remainder of the chapter we denote a composite of two inputs by Z. The A_j, $j \in \{E, K, L\}$, are parameters representing factor-specific levels of technology.[44] The elasticity of substitution between energy E and composite input Z equals $\sigma_{KL,E}$, and $\sigma_{K,L}$ is the elasticity of substitution between inputs K and L. Parameters α and β, $0 < \alpha, \beta < 1$, are share parameters.[45]

When an elasticity of substitution equals unity, the production function involved reduces to a Cobb-Douglas function with the share parameters in (5.1) and (5.2) as production elasticities. From (5.1) and (5.2) it is easy to see that if $\sigma_{KL,E} = \sigma_{K,L}$, then the nested function reduces to a one-level CES production function where all three inputs are equally easy to substitute for each other. On the other hand, if two inputs are not in the same nest, then the elasticity of substitution between these inputs is determined by the two CES elasticities and the cost-share of the composite. Hence a different nesting structure implies different values for the substitution elasticities.

One of the questions to be answered in this chapter is whether a total factor productivity representation of technology in climate policy models is sufficient, or technology trends are input specific. With a purely total factor productivity representation of technology we have $A_E = A_K = A_L$, in which case we can multiply an input-neutral productivity parameter A_Q out of the right-hand side of (5.1). To test for factor-augmenting technological change versus input-neutral total factor productivity growth we need to identify all (factor-specific) technology parameters. As noted in the introduction, this is not possible when the equations to be estimated are derived from ratios of first order conditions. We will show that, using a system of equations derived from cost-minimization, we can not only identify all factor-specific technology parameters but in addition we can explicitly test for input-neutral TFP growth against the null hypothesis of factor-specific technological change.

Following Berndt (1991, p. 457), we assume that our 2-digit industry-level data (see section 5.2) are sufficiently disaggregated to assume that prices are exogenous, and derive our system of equations from the cost function approach. With a two-level CES production function, the cost minimization problem of a firm can be represented as a two-stage problem: in the case of the (KL)E nesting structure we first have to find the optimal demand for K and L per unit of Z, given prices and technology, and then use the resulting relative price of Z to solve for the optimal de-

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[44] Note that we multiplied out any total factor productivity term A_Q and Z-specific technology parameter A_Z. Hence these are included in the factor-specific technology parameters A_j.

[45] The levels of output, inputs, Z, and of the five technology parameters are time- and possibly country- or industry-dependent, but we suppressed the subscripts to ease notation.

mand for E and Z in the upper nest.[46] We present the problem for the upper nest of the (KL)E nesting structure (the problems for the nest with K and L, and for the other nesting structures, are analogous):

$$\min_{E,Z} P_E E + P_Z Z \text{ s.t.}$$
$$\bar{Q} = \left(\alpha(A_E E)^{\frac{\sigma_{KL,E}-1}{\sigma_{KL,E}}} + (1-\alpha)(Z)^{\frac{\sigma_{KL,E}-1}{\sigma_{KL,E}}}\right)^{\frac{\sigma_{KL,E}}{\sigma_{KL,E}-1}}, \tag{5.3}$$

where the price of input j is denoted by P_j, and $\bar{Q}$ is a given output level. From the first order conditions we can derive the cost function $c(P_E, P_Z, Q)$. After applying Shephard's lemma we find the conditional factor demands. Following the literature on climate policy modeling, we assume price-taking behaviour by firms, which implies that the unit cost function gives the price of output. Substituting this result into the conditional factor demands, taking logarithms, and rearranging, gives for input E (the equation for Z is analogous):

$$\ln\left(\frac{E}{Q}\right) = \sigma_{KL,E}\ln\alpha + \left(\sigma_{KL,E}-1\right)\ln A_E + \sigma_{KL,E}\ln\left(\frac{P_Q}{P_E}\right). \tag{5.4}$$

As is well-known in the literature on estimating constant substitution elasticities, not all parameters can be estimated, as usually the equation (or system of equations) to be estimated is under-identified. This is can be seen in (5.4): if we estimate this equation using price and quantity data (by adding an error term to the right-hand side), the first two terms on the right hand side would end up in the constant term and hence the share parameter α and technology parameter A_E cannot be individually identified. After taking first differences (i.e. for each variable X we take $X(t) - X(t-1)$), we get percentage changes in (5.4).[47] Since the first term on the right-hand side was a constant, it drops out, and we can identify the (constant) growth rate of the factor-specific technology parameter from the constant term, using the estimate for the elasticity of substitution. The same procedure can be applied for input Z and the lower nest. This gives us the following four equations for the (KL)E structure, where lower-case letters denote percentage changes:

$$e - q = (\sigma_{KL,E}-1)a_E + \sigma_{KL,E}(p_Q - p_E) \tag{5.5}$$
$$z - q = \sigma_{KL,E}(p_Q - p_Z) \tag{5.6}$$
$$k - z = (\sigma_{K,L}-1)a_K + \sigma_{K,L}(p_Z - p_K) \tag{5.7}$$
$$l - z = (\sigma_{K,L}-1)a_L + \sigma_{K,L}(p_Z - p_L) \tag{5.8}$$

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[46] The weak separability of the nested CES function allows us to first solve for the relative optimal factor demand for the lower nest. Since our functions are homogenous of degree one, we then know the input demand and cost price per unit of Z. This information can subsequently be used to find the optimal levels of E and Z, from which the optimal levels of K and L can be derived.

[47] $\mathrm{d}\ln E(t) = \ln E(t) - \ln E(t-1) \equiv e$ is the discrete time approximation of $\frac{\mathrm{d}\ln E(t)}{\mathrm{d}t} = \frac{\mathrm{d}E(t)}{dt}\frac{1}{E(t)}$, the growth rate or percentage change of E in continuous time. The same procedure is applied to all other variables.

On the left-hand side of each equation we see the percentage change in the ratio of two quantities. On the right-hand side of each equation we first see a term containing an elasticity of substitution, $\sigma_{i,j}$ or $\sigma_{ij,k}$, and a technology parameter a_j (except for (5.6), see footnote 4), and a term consisting of the product of a substitution elasticity and the percentage change of the ratio of two prices. Hence the first equation explains the growth rate of the energy-output ratio $e-q$ from the (negative of the) growth rate of their relative price $p_Q - p_E$, the substitution possibilities $\sigma_{KL,E}$, and the rate of energy-augmenting technological change a_E.

Unfortunately z and p_Z are unobservable, and they can neither be derived using the method used by Prywes (1986) and Chang (1994) (as in that case we would not be able to estimate the technology parameters), nor using the observable prices and quantities of the inputs that form the intermediate input.[48] To circumvent this problem, we add $p_K - p_Q - (p_Z - p_Q)$ to both sides of (5.7), which gives us the growth rate of the share of capital costs in the costs of the intermediate input on the left-hand side:

$$p_K + k - (p_Z + z) = (\sigma_{K,L} - 1)a_K + (\sigma_{K,L} - 1)(p_Z - p_K)). \tag{5.9}$$

We then add $p_Z - p_Q$ to both sides of (5.6), and divide both sides by $\sigma_{KL,E} - 1$, to get

$$p_Q - p_Z = \frac{p_Z + z - (p_Q + q)}{\sigma_{KL,E} - 1}, \tag{5.10}$$

and substitute this into the right-hand side of (5.9) to find

$$\begin{aligned} p_K + k - (p_Z + z) = {} & (\sigma_{K,L} - 1)a_K \\ & + (\sigma_{K,L} - 1)\left(\frac{p_Z + z - (p_Q + q)}{1 - \sigma_{KL,E}} - (p_K - p_Q)\right). \end{aligned} \tag{5.11}$$

Note that $p_K + k - (p_Z + z)$ and $p_Z + z - (p_Q + q)$ are observable changes in cost shares, and we have solved the problem of z and p_Z being unobservable. Applying the same procedure to (5.8) gives us the following system of equations:

$$\begin{aligned} e - q &= (\sigma_{KL,E} - 1)a_E + \sigma_{KL,E}(p_Q - p_E) && (5.12) \\ \widetilde{\theta_{KZ}} &= (\sigma_{K,L} - 1)a_K + \frac{\sigma_{K,L} - 1}{1 - \sigma_{KL,E}}\widetilde{\theta_{ZQ}} + (1 - \sigma_{K,L})(p_K - p_Q) && (5.13) \\ \widetilde{\theta_{LZ}} &= (\sigma_{K,L} - 1)a_L + \frac{\sigma_{K,L} - 1}{1 - \sigma_{KL,E}}\widetilde{\theta_{ZQ}} + (1 - \sigma_{K,L})(p_L - p_Q) && (5.14) \end{aligned}$$

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[48] For example, we cannot construct the growth rate of the capital-labour composite, z, as a weighted average of the growth rates of capital and labour. This would give $z = \theta_{KZ}k + (1 - \theta_{KZ})l$, where the θs are cost shares. However, (2) in growth rates gives $z = \theta_{KZ}(a_K + k) + (1 - \theta_{KZ})(a_L + l)$, where we cannot observe the a_js. Hence constructing a series for z or p_Z using data on prices and quantities of capital and labour only (that is, without knowledge of the technology parameters), will lead to measurement error and hence biased estimates of the coefficients.

where $\widetilde{\theta_{mn}} \equiv p_m + m - (p_n + n)$ is the percentage change of the cost share of input M in the costs of producing N, and (5.13) is (5.11) using the new notation. For the case of the (KL)E nesting structure, this leads to the following model to be estimated:

$$y_1 = \alpha_1 + \beta_1 x_1 + \varepsilon_1 \tag{5.15}$$

$$y_2 = \alpha_2 + \beta_{21} x_{21} + \beta_{22} x_{22} + \varepsilon_2 \tag{5.16}$$

$$y_3 = \alpha_3 + \beta_{31} x_{31} + \beta_{32} x_{32} + \varepsilon_3 \tag{5.17}$$

where the εs are error terms and the dependent variables are $y_1 = e - q$, $y_2 = p_K + k - d\ln(P_K K + P_L L)$ and $y_3 = p_L + l - d\ln(P_K K + P_L L)$, with $d\ln X$ denoting the first difference of the natural logarithm of X. The independent variables are $x_1 = p_Q - p_E$, $x_{21} = x_{31} = d\ln(P_K K + P_L L) - p_Q - q$, $x_{22} = p_K - p_Q$ and $x_{32} = p_L - p_Q$. From (5.13) and (5.14) we see that we have to impose the following cross-equation restrictions when estimating the system: $\beta_{22} = \beta_{32}$ and $\beta_{21} = \beta_{31} = -\beta_{22}/(1-\beta_1)$.[49] We can then derive our parameters as follows: $\sigma_{KL,E} = \beta_1$, $\sigma_{K,L} = 1 - \beta_{22}$, $a_E = \alpha_1/(\beta_1 - 1)$, $a_L = -\alpha_2/\beta_{22}$ and $a_K = -\alpha_3/\beta_{22}$.

Following the analysis above, we see that if we assume that technology is not factor-specific but based on input-neutral total factor productivity (that is if we do not normalize A_Q to 1 and in addition assume that $A_E = A_K = A_L = 1$) we can derive the TFP growth parameter a_Q. For the (KL)E nesting structure this gives:

$$e - q = (\sigma_{KL,E} - 1)a_Q + \sigma_{KL,E}(p_Q - p_E) \tag{5.18}$$

$$\widetilde{\theta_{KZ}} = \frac{\sigma_{K,L} - 1}{1 - \sigma_{KL,E}}\widetilde{\theta_{ZQ}} + (1 - \sigma_{K,L})(p_K - p_Q) \tag{5.19}$$

$$\widetilde{\theta_{LZ}} = \frac{\sigma_{K,L} - 1}{1 - \sigma_{KL,E}}\widetilde{\theta_{ZQ}} + (1 - \sigma_{K,L})(p_L - p_Q) \tag{5.20}$$

Since the last model is a special case of the model with factor-specific technological change, we can test whether technological change is based on input-neutral total factor productivity growth (as modeled by Goulder and Schneider, 1999, Sue Wing, 2003) or factor-specific. To be more precise, we can test for the model of TFP growth by testing $-\alpha_2/\beta_{22} = -\alpha_3/\beta_{32} = 0$.[50]

In addition we can test for specific functional forms. We can test whether the production function is a one-level, non-nested CES by testing the restriction β_{21} $(= \beta_{31}) = 1$. We can test for a Cobb-Douglas function for one of the two levels by testing $\beta_1 = 1$ and $\beta_{22} = \beta_{32} = 0$, respectively.

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[49] Using the weak separability of the nested CES function, we first estimate (5.15) and use the result for β_1 to impose the restriction on β_{21} and β_{22}.

[50] We also tested for the model with TFP growth by testing $\alpha_2 = \alpha_3 = 0$, since both tests are statistically correct but may give different results. Our conclusions are qualitatively unaffected when using this alternative test.

5.2 Econometric model and data

We estimated the system (5.15)-(5.17) for each of our 3 nesting structures. To identify the parameters of our model, we first estimate (5.15) and use the resulting estimate for the elasticity of substitution for the outer nest in the restriction on the system (5.16)-(5.17) (see footnote 5.1). As described below, we have industry-level time series data for 12 countries. We estimate models with industry-specific elasticities and models with country-specific elasticities.[51] That is, we estimate the system (5.15)-(5.17) for each nesting structure with panels for each industry to estimate industry-specific elasticities, and estimate the same system for each nesting structure with panels for each country to estimate country-specific elasticities, which gives us in total 6 systems to estimate. We use country-industry fixed effects (i.e. a dummy for each country-industry combination) and estimated the fixed effects models using least squares dummy variable models. We then tested, for each equation in each model, whether the fixed effects where the same for all country-industry combinations. We were unable to reject this hypothesis for any equation (at the 10% significance level). As a consequence, pooled regressions are more efficient than regressions using fixed effects, and the remainder of the chapter contains results from pooled regressions.

The data are derived from the IEA Energy Balances and from the OECD International Sectoral Database.[52] They form an unbalanced panel for 12 OECD countries, with up to 7 industries (6 sub-industries of the manufacturing industry plus the construction industry), and up to 19 years of observations. The countries involved are Belgium, Canada, Denmark, Finland, France, United Kingdom, Italy, the Netherlands, Norway, Sweden, USA and West-Germany. The industries involved are basic metal products, construction, food & tobacco, textiles & leather, non-metallic minerals, transportation equipment, and the paper, pulp & printing industry. Data come from the time period 1978-1996. We drop the first and last percentile of observations for q, e, l, k, and their prices, to correct for outliers without having to judge on individual observations. This gives us in total 1031 observations.

All prices are in 1990 U.S. dollars, PPP. The price of value added is the numeraire. Industry output is the sum of value added and the value of energy at 1990 market prices. Energy is energy use in kiloton of oil equivalents (IEA Energy Balances). Price of energy is per kiloton of oil equivalent (IEA Energy Balances). Capital is gross capital stock (OECD International Sectoral Database). Price (user cost) of

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[51] We have too few observations per country-industry combination (12 on average, with for some country-industry combinations as few as 6 observations) to estimate elasticities using panels at the combined country-industry level.

[52] We use the same database as Van Soest et al. (2006).

capital is foregone interest plus depreciation minus capital gain. Here the interest rate is the nominal bond rate (IMF, International Financial Statistics), depreciation is the ratio of consumption of fixed capital and gross capital stock (both OECD International Sectoral Database) or 3.5%, capital gain is the percentage change in the ratio of gross capital stock in current national prices and gross capital stock. Labour is total employment in man hours (OECD International Sectoral Database). Price of labour is compensation of employees, per man hour (OECD International Sectoral Database).

5.3 Estimation results

Before we move to our results regarding goodness of fit, the elasticities of substitution and technological change, we first discuss the cross-equation restrictions that were mentioned before.

5.3.1 Cross-equation restrictions

As noted in section 5.1, we have to impose some cross-equation restrictions on the system (5.16)-(5.17) to estimate the elasticity of substitution for the inner nest. Before we did so, we first estimated the unrestricted system for all nesting structures, both for country- and industry-specific elasticities.[53] In most cases, the cross-equation restriction $\beta_{22} = \beta_{32}$ was rejected. More precisely, for the model with country-specific elasticities the restriction was rejected for all countries for the (KL)E and (LE)K nesting structures, and for the (KE)L structure it was rejected for 7 out of 12 countries. For the model with industry-specific elasticities the restriction was rejected for all sectors for the (KL)E and (LE)K nesting structures, and for the (KE)L nesting structure it was rejected for 5 out of 7 industries.

However, the purpose of this chapter is to estimate elasticities of substitution that can be used in the dynamic climate policy modeling literature, by making the exactly the same assumptions as in the climate policy modeling literature. That is, we started from a nested constant returns to scale CES production function, and assumed perfect competition at all levels. Although a 3-input translog production function is much more flexible, it would have given a range of (non-constant) elasticities, which would not be suitable for climate policy models without having to make additional assumptions. We therefore proceed with our analysis, imposing the cross-equation restrictions even for those equations where they are rejected ex ante, to find the parameters of the nested CES production function that fits the

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[53] The results of the unrestricted regressions for the (KL)E nesting structure are reported in the appendix.

Table 5.2: Goodness of fit

	(KL)E	(LE)K	(KE)L
Industry σs	0.4071	0.3363	0.1278
Country σs	0.4055	0.3115	0.1456

Note: R^2 adjusted for degrees of freedom.

data best.

5.3.2 Goodness of fit

As noted in the introduction, the literature on climate policy modeling lacks a systematic comparison of the empirical relevance of the nesting structures (KL)E, (KE)L and (LE)K. We present the goodness of fit of the three nesting structures in table 5.2.

Table 5.2 shows that there are substantial differences in how well each nesting structure fits the data. For both the model with industry-specific elasticities and the model with country-specific elasticities the $\overline{R}^2$ is highest for the (KL)E nesting structure. The (LE)K nesting structure fits the data much better than the (KE)L structure. This is quite surprising, as one might expect the decision on capital investment to be determined jointly with the decision on labour demand or energy demand, instead of the demand for labour to be determined jointly with the demand for energy. Compared to the other nesting structures, the (KE)L structure fits the data poorly.

5.3.3 Elasticities of substitution

Table 5.3 presents our results for the elasticities of substitution. We will discuss them by nesting structure.[54]

The (KL)E nesting structure

Several dynamic climate policy models use the (KL)E or ((KL),(EM)) nesting structure. That is, they first combine capital and labour, and this composite is subsequently combined with energy (or an energy-materials composite) using a different elasticity of substitution. The first column of Table 5.3 shows our estimates for

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[54] We tested whether the elasticities were the same for all countries or all industries. We rejected this hypothesis for all nests and for all nesting structures at the 1% significance level, except for the elasticity of substitution for the outer nest of the (KE)L structure, i.e. $\sigma_{KE,L}$ (both for countries and for industries), and for the inner nest of the (LE)K structure, i.e. $\sigma_{L,E}$ for country elasticities.

Table 5.3: Estimated elasticities of substitution

	(KL)E		(LE)K		(KE)L	
	$\sigma_{KL,E}$	$\sigma_{K,L}$	$\sigma_{LE,K}$	$\sigma_{L,E}$	$\sigma_{KE,L}$	$\sigma_{K,E}$
Industry σs						
Basis metals	0.6454^{**}	0.6190^{**}	0.4990^{**}	0.8889^{**}	0.8866^{**}	0.9606^{**}
	(0.0639)	(0.0212)	(0.0198)	(0.0179)	(0.0417)	(0.0132)
Construction	0.2892^{**}	0.2242^{**}	0.1796^{**}	0.5127^{**}	0.9496^{**}	0.9931^{**}
	(0.0566)	(0.0312)	(0.0308)	(0.0442)	(0.1112)	(0.0026)
Food & Tob.	0.3990^{**}	0.4597^{**}	0.4240^{**}	0.8454^{**}	0.9231^{**}	0.9920^{**}
	(0.0585)	(0.0226)	(0.0223)	(0.0253)	(0.0716)	(0.0051)
Transport Eq.	0.1705^{*}	0.4638^{**}	0.3927^{**}	0.8167^{**}	1.0126^{**}	1.0022^{**}
	(0.0818)	(0.0319)	(0.0323)	(0.0378)	(0.0800)	(0.0008)
Non-metal. Min.	0.2546^{**}	0.4541^{**}	0.3925^{**}	0.8204^{**}	0.9465^{**}	1.0001^{**}
	(0.0653)	(0.0242)	(0.0238)	(0.0262)	(0.0650)	(0.0038)
Paper etc.	0.4489^{**}	0.4103^{**}	0.3518^{**}	0.7997^{**}	0.8907^{**}	0.9945^{**}
	(0.0684)	(0.0220)	(0.0215)	(0.0291)	(0.0706)	(0.0076)
Textiles etc.	0.2944^{**}	0.2737^{**}	0.2320^{**}	0.7852^{**}	1.0440^{**}	0.9987^{**}
	(0.0649)	(0.0192)	(0.0187)	(0.0323)	(0.0728)	(0.0018)
Country σs						
Belgium	0.6053^{**}	0.6154^{**}	0.5379^{**}	0.8566^{**}	1.0328^{**}	0.9984^{**}
	(0.0765)	(0.0375)	(0.0386)	(0.0333)	(0.0759)	(0.0034)
Canada	0.1725	0.5273^{**}	0.3662^{**}	0.7912^{**}	0.8861^{**}	0.9865^{**}
	(0.1231)	(0.0481)	(0.0531)	(0.0453)	(0.0716)	(0.0143)
Denmark	0.4957^{**}	0.4184^{**}	0.4066^{**}	0.8611^{**}	0.8227^{**}	0.9498^{**}
	(0.0947)	(0.0348)	(0.0325)	(0.0327)	(0.0864)	(0.0187)
Finland	0.5415^{**}	0.5525^{**}	0.4495^{**}	0.8530^{**}	0.9465^{**}	0.9882^{**}
	(0.0717)	(0.0290)	(0.0281)	(0.0276)	(0.0623)	(0.0048)
France	0.3518^{**}	0.4200^{**}	0.3842^{**}	0.7886^{**}	1.0526^{**}	1.0003^{**}
	(0.0719)	(0.0278)	(0.0279)	(0.0341)	(0.1004)	(0.0032)
UK	0.2481^{**}	0.2748^{**}	0.2278^{**}	0.7138^{**}	0.8027^{**}	0.9474^{**}
	(0.0764)	(0.0280)	(0.0282)	(0.0427)	(0.0774)	(0.0137)
Italy	0.2417^{**}	0.5216^{**}	0.4651^{**}	0.8037^{**}	0.9218^{**}	0.9799^{**}
	(0.0766)	(0.0353)	(0.0359)	(0.0327)	(0.0845)	(0.0078)
Netherlands	0.1928^{*}	0.2892^{**}	0.2479^{**}	0.8165^{**}	1.0284^{**}	0.9963^{**}
	(0.0936)	(0.0263)	(0.0258)	(0.0448)	(0.0999)	(0.0019)
Norway	0.3255^{**}	0.3800^{**}	0.3276^{**}	0.7728^{**}	0.7821^{**}	0.9182^{**}
	(0.0895)	(0.0288)	(0.0277)	(0.0386)	(0.0861)	(0.0210)
Sweden	0.2531^{**}	0.4655^{**}	0.4087^{**}	0.8165^{**}	1.0348^{**}	1.0010^{**}
	(0.0756)	(0.0254)	(0.0255)	(0.0325)	(0.0828)	(0.0021)
USA	0.5470^{**}	0.3191^{**}	0.2852^{**}	0.8584^{**}	0.9793^{**}	0.9999^{**}
	(0.1100)	(0.0278)	(0.0278)	(0.0488)	(0.1198)	(0.0013)
West-Germany	0.3311^{**}	0.4271^{**}	0.3750^{**}	0.7457^{**}	1.1802^{**}	0.9869^{**}
	(0.0968)	(0.0432)	(0.0418)	(0.0565)	(0.1628)	(0.0157)

Note: Standard errors in parentheses. */** indicates that coefficient differs from zero at 5/1% level of significance.

Table 5.4: Tests for Cobb-Douglas function.[a]

	(KL)E		(LE)K		(KE)L	
	$\sigma_{KL,E}$	$\sigma_{K,L}$	$\sigma_{LE,K}$	$\sigma_{L,E}$	$\sigma_{KE,L}$	$\sigma_{K,E}$
Industry σs						
Basis metals	0.0001	0.0000	0.0000	0.0000	0.0066	0.0029
Construction	0.0000	0.0000	0.0000	0.0000	0.6501	0.0082
Food & Tob.	0.0000	0.0000	0.0000	0.0000	0.2828	0.1161
Transport Eq.	0.0000	0.0000	0.0000	0.0000	0.8752	0.0071
Non-metal. Min.	0.0000	0.0000	0.0000	0.0000	0.4107	0.9778
Paper etc.	0.0000	0.0000	0.0000	0.0000	0.1216	0.4695
Textiles etc.	0.0000	0.0000	0.0000	0.0000	0.5459	0.4682
Country σs						
Belgium	0.0000	0.0000	0.0000	0.0000	0.6659	0.6385
Canada	0.0000	0.0000	0.0000	0.0000	0.1117	0.3441
Denmark	0.0000	0.0000	0.0000	0.0000	0.0403	0.0074
Finland	0.0000	0.0000	0.0000	0.0000	0.3905	0.0159
France	0.0000	0.0000	0.0000	0.0000	0.6000	0.9284
UK	0.0000	0.0000	0.0000	0.0000	0.0110	0.0001
Italy	0.0000	0.0000	0.0000	0.0000	0.3553	0.0104
Netherlands	0.0000	0.0000	0.0000	0.0000	0.7759	0.0549
Norway	0.0000	0.0000	0.0000	0.0000	0.0116	0.0001
Sweden	0.0000	0.0000	0.0000	0.0000	0.6745	0.6451
USA	0.0000	0.0000	0.0000	0.0038	0.8627	0.9203
West-Germany	0.0000	0.0000	0.0000	0.0000	0.2687	0.4034

[a] Two-sided p-values for H_0: elasticity equal to 1.

the elasticity of substitution between energy and the capital-labour composite. We see a considerable amount of variation over industries and countries. The industry estimates range from 0.17 to 0.65, while the country estimates range from 0.17 to 0.61. Note that we cannot reject perfect complementarity (i.e. an elasticity equal to zero) between energy and the capital-labour composite for Canada. The elasticities for capital and labour are reported in the second column and show quite some variation as well, with estimates ranging from 0.22 to 0.61 for the industry elasticities and from 0.27 to 0.62 for the country estimates.

Table 5.4 presents the probability values for the two sided tests whether each elasticity is equal to one, in which case we would have a Cobb-Douglas production function.[55] For all countries and industries the null-hypothesis of a unit elasticity is rejected.

In addition we tested for common elasticities over the two nests (i.e. $\sigma_{KL,E} = \sigma_{K,L}$).

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[55] A p-value smaller than 0.05 implies that we can reject the null-hypothesis at the 5% significance level.

Table 5.5: Tests for common elasticities (no nesting).[a]

	(KL)E	(LE)K	(KE)L
Industry σs			
Basis metals	0.6944	0.0000	0.0909
Construction	0.3146	0.0000	0.6956
Food & Tob.	0.3328	0.0000	0.3368
Transport Eq.	0.0009	0.0000	0.8970
Non-metal. Min.	0.0043	0.0000	0.4106
Paper etc.	0.5907	0.0000	0.1438
Textiles etc.	0.7598	0.0000	0.5345
Country σs			
Belgium	0.9059	0.0000	0.6511
Canada	0.0074	0.0000	0.1693
Denmark	0.4440	0.0000	0.1505
Finland	0.8864	0.0000	0.5045
France	0.3766	0.0000	0.6021
UK	0.7429	0.0000	0.0659
Italy	0.0009	0.0000	0.4941
Netherlands	0.3217	0.0000	0.7480
Norway	0.5615	0.0000	0.1252
Sweden	0.0078	0.0000	0.6832
USA	0.0450	0.0000	0.8636
West-Germany	0.3655	0.0000	0.2375

[a] Two-sided p-values for H_0: $\sigma_{i,j} = \sigma_{ij,k}$.

That is, we tested whether the production function could have a single elasticity of substitution and hence could be non-nested. As is shown in Table 5.5, we cannot reject a non-nested production function for 5 out of 7 industries and 8 out of 12 countries.

The (LE)K nesting structure

The substitution elasticities for both nests of the (LE)K nesting structure differ significantly from zero for all countries and all industries. Values for $\sigma_{LE,K}$ range from 0.18 to 0.50 for the industry estimates and from 0.23 to 0.54 for the country estimates. Industry and country elasticities for the inner nest range from 0.51 to 0.89 and from 0.71 to 0.86, respectively. For all elasticities we can reject the null of a unit elasticity at the 1% level. Contrary to the (KL)E structure we can reject the null-hypothesis of a common elasticity for both nests for all countries and all industries for the (LE)K nesting structure.

The (KE)L nesting structure

The (KE)L nesting structure, which has the lowest $\overline{R}^2$, shows remarkably high elasticities when compared to the (KL)E and (LE)K nesting structures. For the outer nest, $\sigma_{KE,L}$, the values range from 0.89 to 1.04 for the industry estimates, and from 0.78 to 1.18 for the country estimates (see Table 5.3). The values for the elasticity of substitution between capital and energy range from 0.92 to 1.001, for countries and from 0.96 to 1.002 for industries.

When we test for Cobb-Douglas production functions for the outer nest, we can only reject it for the basis metals industry (at the 1% significance level) and for Denmark, the UK and Norway (at the 5% level, but not at the 1% level). For the inner nest we reject a Cobb-Douglas production function for 5 countries and 3 industries. We cannot reject a common elasticity for both nests, for all industries and for all countries.

5.3.4 Technological change

The models in Table 5.1 not only differ in nesting structure and sizes of substitution elasticities, but also in the way productivity improvements enter the production function. We saw in Table 5.1 that, of those models with endogenous technological change, 4 models use energy-specific technological change, 2 models use industry-specific total factor productivity changes and 1 model uses factor-specific technological change. Since all these models either use a (KL)E or (KLE) nesting structure, and since this is the structure that fits the data best, we focus on the results for technological change for the (KL)E nesting structure (recall that for the (KL)E nesting structure we could not reject a (KLE) structure for most countries and most industries).

Table 5.6 shows the (constant) factor-specific technology trends for the (KL)E nesting structure. We find rates of energy-augmenting technological change of 1.2-2.8% per year. Interestingly we find the highest rate of energy-specific technological change (over industries) in the energy-intensive basis metals industry. The rates of labour-augmenting technological change are generally higher than the rate of energy-augmenting technological change, with values around 3%, while the rates of capital-augmenting technological change are found to be negative and around -2.4%.[56]

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[56] The negative rate of capital-augmenting technological change is intriguing. Acemoglu (2003) shows that when the income share of capital is below its steady state level, technological change will be capital-using, i.e. aimed at increasing the cost-share of capital. When the elasticity of substitution between capital and labour is smaller than 1, this will lead to $a_K - a_L$ being negative. Our data as well as our empirical results match this theory. In the late 1970s (the beginning of our sample) the cost-share of capital was low, as the return on capital was low due to the oil crises (overcapacity).

Table 5.6: Rates of factor-specific technological change, (KL)E nesting structure

	Energy	Labour	Capital
Industry σs			
Basis metals	0.0283^{**}	0.0420^{**}	-0.0337^{**}
	(0.0098)	(0.0048)	(0.0039)
Construction	0.0141^{**}	0.0206^{**}	-0.0165^{**}
	(0.0044)	(0.0023)	(0.0018)
Food & Tob.	0.0167^{**}	0.0296^{**}	-0.0238^{**}
	(0.0053)	(0.0033)	(0.0026)
Transport Eq.	0.0121^{**}	0.0298^{**}	-0.0239^{**}
	(0.0039)	(0.0035)	(0.0028)
Non-metal. Min.	0.0135^{**}	0.0293^{**}	-0.0235^{**}
	(0.0042)	(0.0033)	(0.0026)
Paper etc.	0.0182^{**}	0.0271^{**}	-0.0218^{**}
	(0.0060)	(0.0030)	(0.0023)
Textiles etc.	0.0142^{**}	0.0220^{**}	-0.0177^{**}
	(0.0044)	(0.0023)	(0.0019)
Country σs			
Belgium	0.0262^{**}	0.0409^{**}	-0.0349^{**}
	(0.0092)	(0.0057)	(0.0048)
Canada	0.0125^{**}	0.0332^{**}	-0.0284^{**}
	(0.0041)	(0.0048)	(0.0040)
Denmark	0.0205^{**}	0.0270^{**}	-0.0231^{**}
	(0.0070)	(0.0033)	(0.0026)
Finland	0.0226^{**}	0.0351^{**}	-0.0300^{**}
	(0.0075)	(0.0043)	(0.0036)
France	0.0160^{**}	0.0271^{**}	-0.0232^{**}
	(0.0050)	(0.0031)	(0.0026)
UK	0.0138^{**}	0.0217^{**}	-0.0185^{**}
	(0.0043)	(0.0024)	(0.0019)
Italy	0.0136^{**}	0.0329^{**}	-0.0281^{**}
	(0.0042)	(0.0041)	(0.0035)
Netherlands	0.0128^{**}	0.0221^{**}	-0.0189^{**}
	(0.0040)	(0.0025)	(0.0020)
Norway	0.0153^{**}	0.0254^{**}	-0.0217^{**}
	(0.0049)	(0.0029)	(0.0023)
Sweden	0.0138^{**}	0.0294^{**}	-0.0251^{**}
	(0.0043)	(0.0034)	(0.0028)
USA	0.0228^{**}	0.0231^{**}	-0.0197^{**}
	(0.0086)	(0.0026)	(0.0021)
West-Germany	0.0155^{**}	0.0274^{**}	-0.0235^{**}
	(0.0050)	(0.0035)	(0.0030)

Note: Standard errors in parentheses. */** indicates that coefficient differs from zero at 5/1% level of significance.

Furthermore, we find that $a_K - a_L$ is indeed negative, along with $\sigma_{K,L} < 1$. In Acemoglu's framework, the rate of capital-augmenting technological change can then be negative when gross investment in this type of technological change is not enough to compensate for knowledge depreciation.

Table 5.7: Tests for $a_i = a_j$, for (KL)E structure

	$a_E = a_L$	$a_E = a_K$	$a_L = a_K$
Industry σs			
Basis metals	0.2099	0.0000	0.0000
Construction	0.1923	0.0000	0.0000
Food & Tob.	0.0380	0.0000	0.0000
Transport Eq.	0.0007	0.0000	0.0000
Non-metal. Min.	0.0029	0.0000	0.0000
Paper etc.	0.1834	0.0000	0.0000
Textiles etc.	0.1167	0.0000	0.0000
Country σs			
Belgium	0.1761	0.0000	0.0000
Canada	0.0010	0.0000	0.0000
Denmark	0.4010	0.0000	0.0000
Finland	0.1450	0.0000	0.0000
France	0.0583	0.0000	0.0000
UK	0.1059	0.0000	0.0000
Italy	0.0012	0.0000	0.0000
Netherlands	0.0478	0.0000	0.0000
Norway	0.0769	0.0000	0.0000
Sweden	0.0044	0.0000	0.0000
USA	0.9772	0.0000	0.0000
West-Germany	0.0508	0.0000	0.0000

Note: Two-sided p-values for H_0: $a_i = a_j$.

If we write (5.1) and (5.2) and the first-order condition with respect to each input in percentage changes, we can derive the effect of input-augmenting technological change on the cost-share of each input.[57] That is, we can show, for each input, whether technological change is input-using or input-saving. Our estimates for the (constant) rates of technological change imply that technological change has been labour- and energy-saving, and capital-using (as explained in footnote 57, this does not directly follow from the signs of the rates of factor-specific technological change).

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[57] Equations (5.1) and (5.2) in percentage changes give $q = a_Q + \theta_{EQ}(a_E + e) + (1 - \theta_{EQ})z$ and $z = \theta_{LZ}(a_L + l) + (1 - \theta_{LZ})(a_K + k)$. The first-order condition with respect to energy gives $\alpha\frac{\sigma_{KL,E}-1}{\sigma_{KL,E}} A_Q^{(\sigma_{KL,E}-1)/\sigma_{KL,E}} A_E(A_E E)^{-1/\sigma_{KL,E}} Q^{(1-\sigma_{KL,E})/\sigma_{KL,E}} = P_E$. After multiplying both sides with E/Q and rewriting into percentage changes, we find $\widetilde{\theta_{EQ}} = \frac{1-\sigma_{KL,E}}{\sigma_{KL,E}}(z - a_E - e)$. Substituting the first two expressions into the latter we find $\widetilde{\theta_{EQ}} = \frac{1-\sigma_{KL,E}}{\sigma_{KL,E}}(1-\theta_{EQ})(\theta_{LZ}(a_L+l)+(1-\theta_{LZ})(a_K+k)-a_E-e)$. Using the results of our empirical analysis and observed cost-shares from our data, and keeping input levels constant, we find $\widetilde{\theta_{EQ}} = \frac{1-\sigma_{KL,E}}{\sigma_{KL,E}} \cdot 0.95 \cdot (0.65 \cdot 0.03 + 0.35 \cdot (-0.024) - 0.02) < 0$, since $\sigma_{KL,E} < 1$. Hence, energy-augmenting technological change reduces the cost-share of energy and is hence energy-saving. The results for capital and labour can be found using the same procedure.

For our purpose it is interesting to see whether the technology trends for the three inputs differ from each other. Table 5.7 presents, for each country and each industry, tests whether the technology trends are equal. We can reject that the rate of energy-augmenting technological change and the rate of labour-augmenting technological change are equal, for 3 out of 7 industries and 4 out of 12 countries (at the 5% significance level). When testing the equality of either of these two technology trends and the rate of capital-augmenting technological change, we can reject the null-hypothesis for all industries and countries. We therefore conclude that rates of factor-specific technological change tend to differ over factors.

As noted in Section 5.1, we can test for the model of input-neutral total factor productivity growth by testing $a_L = a_K = 0$. As can be inferred from Tables 5.6 and 5.7, we can reject $a_L = a_K = 0$ for all countries and industries for the (KL)E nesting structure.

5.4 Discussion

Comparing the results of the previous section with the climate policy models in Table 5.1, we can draw four conclusions.

The first conclusion refers to the nesting structure chosen by the climate policy models. Nearly all models have capital and labour in the same nest. This nesting structure is supported by our results as the (KL)E nesting structure seems to fit the data best. The (KE)L nesting structure, as used in Burniaux et al. (1992), on the other hand, performs rather poorly in terms of goodness of fit. The argument that the demand for capital and energy is determined jointly, as machines use energy, is only partly valid. Capital is not just the stock of available machines, but money invested in general, or foregone consumption. Our results suggest that, given the (KL)E nesting structure, substitution elasticities may be the same for both nests for several countries and industries. Indeed, several of the models in Table 5.1 do not have a separate nest for the capital-labour composite, but model both inputs together with energy in a non-nested function. Hence our results support the nesting choice for most of the models in Table 5.1.

It should be noted, however, that our results suggest that there is considerable variation over countries and industries in substitution possibilities. Our second conclusion therefore is that both the sizes of the elasticities, and whether the nesting structure is (KL)E or non-nested KLE, vary considerably over both countries and industries.

Our third conclusion refers to the sizes of the elasticities of substitution. Several climate models that use a (KL)E or KLE (or KLEM) nesting structure use a unit elasticity of substitution for (part of the) production function. However, our results for the (KL)E nesting structure, which is the nesting structure that fits the data best, show that we can reject the Cobb-Douglas function for all industries and for all countries. We find that $\sigma_{KL,E}$ ranges from 0.1 to 0.6, while $\sigma_{K,L}$ ranges from 0.2 to 0.6. The recent literature on capital-labour production functions rejects unit elasticities, in favour of smaller values, as well (see e.g. Antràs (2004) and references therein). We therefore conclude that the elasticities of substitution in (parts of) the production functions in some of the papers in Table 5.1 are too high.

Our results for factor-specific technological change suggest that technology trends differ significantly over inputs. Energy, labour and capital all have a significant rate of technological change, and they generally differ significantly from each other. This is ignored in climate policy models that use Cobb-Douglas production functions, since they do not allow technological change to affect relative marginal productivities of inputs. In addition, our results go against models with input-neutral total factor productivity growth. Our fourth conclusion is therefore that most papers in Table 5.1 put too many restrictions on their models regarding the possibilities for technological change.

What are the possible effects of elasticities that are too high, and of a rigid way of modeling changes in the production isoquant, on the results that are found by climate policy models? First of all, changes in the elasticity of substitution affect the model results when there is no endogenous technological change. As noted in the introduction, Jacoby et al. (2006) found that the MIT EPPA model is most sensitive to changes in the elasticity of substitution between the capital-labour composite and energy. Both the model of Goulder and Schneider (1999) and the model of Popp (2004) use a unit elasticity, which is rejected by the data.

Secondly the higher an elasticity of substitution, the easier it is to substitute away from an input that faces an increase in its relative price, and the lower will be the need to invest in input-saving technological change. As a consequence, climate policy models that use elasticities of substitution that are too high may underestimate the role of endogenous technological change in reducing the costs of climate policy.

Furthermore, models with a Cobb-Douglas production function neglect the role of factor-specific technological change, since with a Cobb-Douglas production function technological change does not affect the relative marginal productivity of inputs. It is therefore impossible to aim innovations at energy-saving technologies: changes in the production isoquant are always input-neutral productivity improvements. Hence the costs of achieving a certain improvement in the productivity of energy may be lower when moving away from a unit elasticity of substitution.

Finally, energy-specific technological change and input-neutral total factor productivity growth (even at the industry or country level) all take away degrees of freedom from an economy. Adding additional flexibility to a model could lead to a lower burden of climate policy on an economy.

5.5 Summary and conclusions

This chapter contributes to the literature on climate policy modeling by estimating nested CES production functions using capital, labour and energy as inputs. We find that the nesting structure in which first capital and labour are combined using a CES function, and then this composite of capital and labour is combined with energy in a second CES function, fits the data best. For this (KL)E nesting structure we were, for most countries and most industries, not able to reject the hypothesis that the elasticities are equal for both nests. The (KL)E nesting structure, or its non-nested form with equal elasticities for both nests, is used by most models in the applied climate policy modeling literature. However, our estimates for the elasticities of substitution vary substantially over countries and over industries, and are lower than those used in some of the models. In addition we explicitly reject unit elasticities of substitution (i.e. Cobb-Douglas production functions). Regarding technological change, we find factor-specific growth rates that are significant and that mostly significantly differ from each other. We reject input-neutral total factor productivity growth (in favour of factor-specific technological change) and 'only energy-augmenting technological change', both of which are used by several papers in the climate policy literature.

Given that lower elasticities imply that it becomes harder to substitute away from energy, and given that most models in the climate policy modeling literature put too many restrictions on their models, we suggest that the role of endogenous technological change in reducing the costs of climate policy may be bigger than has been found by some climate policy models. Whether this claim holds, should of course be tested by adapting the models in Table 5.1 to our empirical findings, and comparing the additional effect of endogenous technological change in the original model with that from the adapted model.

5.A Appendix: Estimates for (KL)E without cross-equation restrictions

As noted in section 5.1, we need to estimate the system (5.15)-(5.17) with cross-equation restrictions. However, as noted in section 5.3.1, these cross-equation restrictions are rejected for most of our regressions. We decided to continue with our analysis using regressions with restrictions that are rejected *ex ante*, because the purpose of the chapter is to provide estimates that are as close as possible to the models used in the climate policy modeling literature.

In this appendix, we present the estimation results for the inner nest of the (KL)E model, that is for the parameters that determine $\sigma_{K,L}$ (note that the estimates for $\sigma_{KL,E}$ are not affected by the cross-equation restrictions). We present the estimates of the parameters β_{21}, β_{22}, β_{31} and β_{32} for the unrestricted model in the second to fifth column of Table 5.8. Note that we can only report estimates of the βs, not of the elasticities themselves, since all parameters are inter-dependent in the restricted regressions: $\beta_{21} = \beta_{22}/(1-\sigma_{KL,E}) = \beta_{31} = \beta_{32}/(1-\sigma_{KL,E})$. Since these restrictions are rejected *ex post* in the unrestricted regression, we cannot meaningfully relate the parameter estimates from the unrestricted regression to elasticities from the restricted regression. However, we can compare the estimated βs of the unrestricted system with those of the restricted system, and we report the latter estimates in the last two columns of Table 5.8. The parameters reported in the last two columns are the basis for the elasticities in the first two columns of Table 5.3, where $\sigma_{K,L} = 1-\beta_{22} = 1-\beta_{32} = 1-\beta_{21}/(\sigma_{KL,E}-1) = 1-\beta_{31}/(\sigma_{KL,E}-1)$.

Although 60 out of 76 parameters in the unrestricted regression have the same sign as the parameter from the restricted regression, the restriction $\beta_{22} = \beta_{32}$ is rejected for all industries and countries in the (KL)E specification. Having to impose restrictions seems to be the price to be paid to get estimates based on the nested CES functions that are used in the CGE models of the climate policy modeling literature.

Table 5.8: Estimated parameters without and with cross-equation restrictions, for inner nest of (KL)E

	Unrestricted model				Restricted model	
	β_{21}	β_{22}	β_{31}	β_{32}	$\beta_{21} = \beta_{31}$	$\beta_{22} = \beta_{32}$
Industry βs						
Basis metals	-0.9356^{**}	0.1033^{*}	-0.26391^{*}	0.4288^{**}	-1.0746^{**}	0.3810^{**}
	(0.1298)	(0.0453)	(0.1157)	(0.0222)	(0.0598)	(0.0212)
Construction	0.7496	0.0597	0.0886	0.8219^{**}	-1.0914^{**}	0.7758^{**}
	(1.9199)	(0.1102)	(1.6161)	(0.0298)	(0.0439)	(0.0312)
Food & Tob.	-0.8686^{*}	0.0721	−0.5290	0.5724^{**}	-0.8989^{**}	0.5403^{**}
	(0.4428)	(0.0715)	(0.3721)	(0.0217)	(0.0376)	(0.0226)
Transport Eq.	-4.2901^{*}	0.0094	2.2503	0.5912^{**}	-0.6464^{**}	0.5362^{**}
	(2.0130)	(0.0801)	(1.7363)	(0.0323)	(0.0384)	(0.0319)
Non-metal. Min.	−0.3931	−0.0061	-0.5567^{**}	0.5964^{**}	-0.7324^{**}	0.5459^{**}
	(0.2296)	(0.0679)	(0.1869)	(0.0234)	(0.0324)	(0.0242)
Paper etc.	-0.3802^{*}	0.0139	-0.5549^{**}	0.6350^{**}	-1.0701^{**}	0.5897^{**}
	(0.1810)	(0.0748)	(0.1452)	(0.0211)	(0.0400)	(0.0220)
Textiles etc.	−1.1104	−0.0466	0.8596	0.7556^{**}	-1.0293^{**}	0.7263^{**}
	(0.6930)	(0.0717)	(0.5996)	(0.0185)	(0.0272)	(0.0192)
Country βs						
Belgium	0.2246	−0.1324	-1.0397^{**}	0.4629^{**}	-0.9745^{**}	0.3846^{**}
	(0.4856)	(0.0833)	(0.3889)	(0.0384)	(0.0950)	(0.0375)
Canada	−0.2034	0.0429	-1.3071^{**}	0.6519^{**}	-0.5713^{**}	0.4727^{**}
	(0.3582)	(0.0767)	(0.3037)	(0.0544)	(0.0581)	(0.0481)
Denmark	-1.7132^{**}	0.2799^{**}	-1.2850^{**}	0.6097^{**}	-1.1531^{**}	0.5816^{**}
	(0.3426)	(0.0983)	(0.2928)	(0.0356)	(0.0690)	(0.0349)
Finland	-0.9521^{**}	0.0448	−0.2817	0.4937^{**}	-0.9759^{**}	0.4475^{**}
	(0.1819)	(0.0644)	(0.1680)	(0.0303)	(0.0623)	(0.0290)
France	−0.4672	−0.0815	-0.8176^{*}	0.6150^{**}	-0.8949^{**}	0.5800^{**}
	(0.4516)	(0.1001)	(0.3894)	(0.0271)	(0.0429)	(0.0278)
UK	-1.2017^{*}	0.2001^{*}	-1.1595^{*}	0.7746^{**}	-0.9645^{**}	0.7252^{**}
	(0.5409)	(0.0784)	(0.4725)	(0.0282)	(0.0373)	(0.0280)
Italy	-0.8379^{*}	0.0620	-0.6129^{*}	0.5243^{**}	-0.6309^{**}	0.4784^{**}
	(0.3399)	(0.0855)	(0.2960)	(0.0357)	(0.0465)	(0.0353)
Netherlands	-1.1946^{*}	−0.0278	0.0428	0.7337^{**}	-0.8806^{**}	0.7108^{**}
	(0.5779)	(0.0984)	(0.5387)	(0.0267)	(0.0325)	(0.0263)
Norway	-0.5387^{**}	0.1183	-0.5191^{**}	0.6460^{**}	-0.9191^{**}	0.6200^{**}
	(0.1991)	(0.0944)	(0.1644)	(0.0283)	(0.0426)	(0.0288)
Sweden	−0.4527	−0.0722	−0.3206	0.5792^{**}	-0.7156^{**}	0.5345^{**}
	(0.2324)	(0.0823)	(0.2027)	(0.0250)	(0.0340)	(0.0254)
USA	0.3689	−0.0240	−0.6620	0.7144^{**}	-1.5030^{**}	0.6809^{**}
	(0.6153)	(0.1185)	(0.5339)	(0.0270)	(0.0615)	(0.0278)
West-Germany	−0.7254	−0.2078	0.1306	0.5893^{**}	-0.8565^{**}	0.5729^{**}
	(0.4651)	(0.1620)	(0.4221)	(0.0426)	(0.0646)	(0.0432)

Note: Standard errors in parentheses. */** indicates that coefficient differs from zero at 5/1% level of significance.

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Samenvatting: Klimaatbeleid en economische dynamica – de rol van substitutie en technologische verandering

In de laatste jaren is klimaatverandering een ingeburgerd begrip geworden. Het onderwerp keert regelmatig terug in het nieuws, en in 2007 werd de Nobelprijs voor de vrede zelfs toegekend aan het Intergouvernementele Panel over Klimaatverandering (IPCC) en aan Al Gore, voor hun inspanningen om de kennis over klimaatverandering te vergroten en te verspreiden.

Klimaatbeleid draait om twee soorten overheidsmaatregelen. Ten eerste zijn er maatregelen om klimaatverandering tegen te gaan. Deze maatregelen zijn er op gericht de uitstoot van broeikasgassen, zoals koolstofdioxide (CO_2) te verminderen. Dit kan door de uitstoot van broeikasgassen te belasten (door een hogere prijs zal de vraag dalen), of door een stelsel van verhandelbare emissierechten, gekoppeld aan een bovengrens op de totale hoeveelheid CO_2 emissies. Ten tweede zijn er maatregelen om de gevolgen van klimaatverandering voor mensen en hun omgeving te verminderen (bijvoorbeeld door dijken te verhogen in de strijd tegen de gevolgen van een stijging van de zeespiegel).

In dit proefschrift wordt nader ingegaan op de eerste groep van overheidsmaatregelen. Om preciezer te zijn wordt bekeken hoe beleid dat gericht is op de reductie van de uitstoot van broeikasgassen voor de opwekking van energie (door de verbranding van fossiele brandstoffen zoals kolen, olie en gas), het handelen van economische agenten (met name de producenten van energie en de eigenaren van fossiele brandstoffen) beïnvloedt. Enkele vragen die aan bod komen, zijn: Is het altijd optimaal om, als we CO_2 emissies willen verminderen, relatief minder olie en meer van het schonere gas te gaan gebruiken? Is het van tevoren aankondigen van klimaatbeleid, zodat bedrijven zich erop kunnen voorbereiden, altijd verstandig om te doen? Zullen landen die niet aan klimaatbeleid doen altijd hun emissies verhogen in reactie op de emissiereducties van landen met klimaatbeleid?

Deze vragen draaien om de dynamische reacties van economische agenten (producenten, consumenten) op klimaatbeleid. Dat wil zeggen, we kijken naar de veranderingen in de beslissingen van agenten als gevolg van klimaatbeleid, en hoe deze veranderingen invloed uitoefenen op economische uitkomsten (zoals de vraag naar en productie van fossiele brandstoffen en de daaraan verbonden uitstoot van kooldioxide; de beslissing om te investeren in schone technologieën). Hierbij kijken we met name naar de rol die substitutie (het vervangen van de ene productiefactor door de andere) en technologische verandering spelen.

Naast het eerste, inleidende, hoofdstuk bestaat dit proefschrift bestaat uit 2 delen, die ieder 2 hoofdstukken bevatten. In de rest van deze samenvatting wordt nader op deze laatste 4 hoofdstukken in gegaan.

Deel I: Klimaatbeleid en de optimale extractie van fossiele brandstoffen

In hoofdstuk 2 en 3 van het proefschrift staat het feit dat fossiele brandstoffen niet-hernieuwbare hulpbronnen zijn, centraal. Dat wil zeggen: we gaan er van uit dat als we nu een vat olie (of een ton kolen, of een kubieke meter gas) uit de grond halen en verbruiken, er minder olie (kolen, gas) beschikbaar is voor de toekomst. De 'productie' van fossiele brandstoffen door de natuur is immers een proces van miljoenen jaren, en zowel voor consumenten (bijvoorbeeld bij de benzinepomp) als voor producenten (olie-eigenaren in het Midden-Oosten, maar ook de Nederlandse staat als eigenaar van de Nederlandse aardgasvelden) is dit een te lange tijdshorizon om rekening mee te houden. Het feit dat fossiele brandstoffen niet-hernieuwbaar zijn, heeft grote gevolgen voor het optimale tijdspad voor de extractie (het uit de grond halen) van fossiele brandstoffen. Voor de eigenaren van de brandstoffen betekent dit dat ze moeten afwegen of ze hun product dit jaar verkopen of in de toekomst. Aangezien producenten van consumptiegoederen de energie zowel dit jaar als volgend jaar nodig hebben, moeten de eigenaren van de brandstoffen een prikkel hebben om zowel dit jaar als volgend jaar hun product te verkopen. Dit kan, in het eenvoudigste (Hotelling-)model, alleen als de prijs van de grondstoffen groeit met de rentevoet. Immers, als de prijs van hun product dit jaar hoger is dan volgend jaar, zullen ze alles nu uit de grond halen en verkopen, en de opbrengst op de bank zetten. Indien echter de prijs volgend jaar hoger is, zullen ze dit jaar niets verkopen en wachten tot volgend jaar. De grondstofeigenaren zijn indifferent tussen deze twee opties wanneer de prijs groeit met de rentevoet (gelijke netto contante waarde).

In het eerste deel van het proefschrift gaan we er van uit dat consumenten gelukkiger zijn naar mate ze meer consumeren (maar met dalend marginaal nut), en dat ze liever vandaag een euro ontvangen dan volgend jaar. Voor de consumptie van fossiele brandstoffen betekent dit (1) dat op ieder tijdstip geldt: hoe meer consumptie, hoe hoger het nut van de consument; (2) dat we als we nu alles uit de grond halen en gebruiken, we volgend jaar niks meer hebben; (3) dat de consument meer waarde hecht aan consumptie dit jaar dan aan consumptie volgend jaar. Voor een gegeven voorraad fossiele brandstoffen betekent dit dat het optimaal is om over de tijd steeds minder uit de grond te halen (consumenten hechten immers minder waarde aan consumptie in de toekomst dan aan consumptie in het heden), en dat het optimaal is om door de tijd de totale voorraad op te maken. Als we door de jaren heen de totale voorraad niet op zouden maken, zouden de eigenaren ervan meer kunnen verdienen door op een eerder tijdstip meer uit de grond te halen.[58]

In hoofdstuk 2 en 3 kijken we naar de gevolgen van klimaatbeleid voor de optimale extractiepaden van fossiele brandstoffen.

Hoofdstuk 2: Klimaatbeleid en de optimale extractie van fossiele brandstoffen die verschillen in hun CO_2-gehalte

Wanneer de overheid CO_2-emissies wil terugdringen, kan ze een belasing op CO_2, of een stelsel van verhandelbare emissierechten gekoppeld aan een limiet aan de totale CO_2-uitstoot, invoeren. In beide gevallen krijgen CO_2-emissies een prijs. Kolen, olie en gas verschillen in hun CO_2-gehalte. Per eenheid energie, bijvoorbeeld via de productie van electriciteit, komt er meer CO_2 uit kolen dan uit olie, en meer CO_2 uit olie dan uit gas. Per eenheid energie wordt kolen bij een prijs voor CO_2-emissies dus het zwaarst belast. Deze verandering in de relatieve prijs zorgt voor een verandering in de relatieve vraag naar de verschillende brandstoffen.

Een (statisch) model dat probeert te beschrijven hoe consumenten en producenten reageren op de prijs voor emissies, maar waarin geen rekening wordt gehouden met de eigenschap dat fossiele brandstoffen niet-hernieuwbaar zijn, zou dan als uitkomst geven dat het optimaal is om in reactie op de belasting relatief minder kolen en olie, en relatief meer gas te gaan gebruiken. In hoofdstuk 2 gebruiken we een dynamisch model waarin met deze eigenschap wel rekening wordt gehouden. In het model zijn twee fossiele brandstoffen, die verschillen in hun CO_2-gehalte (bijvoorbeeld kolen en gas), imperfecte substituten in de productie van een consumptiegoed (d.w.z., het is niet eenvoudig om bij een constant productieniveau

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[58] In werkelijkheid zien we dat over de tijd niet steeds minder, maar juist steeds meer fossiele brandstoffen uit de grond worden gehaald. In dit proefschrift houden we geen rekening met een groeiende, en steeds welvarender, wereldbevolking en de daaraan verbonden groeiende vraag naar fossiele brandstoffen, noch met de ontdekking van nieuwe olievelden en nieuwe exploratie- en winningtechnologieën. Dit heeft geen invloed op de kern van de conclusies van het proefschrift.

meer van de ene brandstof en minder van de andere brandstof te gebruiken). Vervolgens wordt de economie geconfronteerd met een constante limiet op de jaarlijkse uitstoot van CO_2 ('Kyoto-voor-altijd'). Dit leidt tot een prijs voor CO_2 uitstoot.

Gezien het feit dat consumenten nog steeds zoveel mogelijk consumptiegoederen willen, ondanks de limiet op emissies, is het zaak voor de producenten van consumptiegoederen om de productie per eenheid CO_2 zo groot mogelijk te maken. Dit betekent dat naast de CO_2-uitstoot per eenheid energie, ook de productiviteit (in termen van consumptiegoederen) per eenheid energie een rol speelt. Deze productiviteit verschilt voor de twee fossiele brandstoffen, en hangt onder andere af van hun relatieve voorraden (relatieve schaarste), en van de substitutiemogelijkheden. In een wereld zonder klimaatbeleid geldt: hoe groter de voorraad van een brandstof is voordat klimaatbeleid wordt ingevoerd, des te groter zal de productie en consumptie ervan zijn (omdat de eigenaren de totale voorraad willen verkopen over de tijd). Tegelijkertijd geldt voor een brandstof die in relatief grote hoeveelheden wordt gebruikt dat het een lage marginale productiviteit heeft, gegeven de beperkte mogelijkheid tot substitutie van de ene brandstof naar de andere. Relatieve schaarste (de verhouding van de voorraden van de twee brandstoffen) is zodoende mede bepalend voor de (marginale) productiviteit van een brandstof.

Om aan de emissielimiet te voldoen kunnen producenten van consumptiegoederen besluiten om meer van de schonere brandstof en minder van de meer vervuilende brandstof te gaan gebruiken (substitutie), of ze kunnen besluiten minder van hun producten te produceren zodat ze minder brandstoffen nodig hebben, of een combinatie van beide. In alle gevallen worden de eigenaren van de fossiele brandstoffen geconfronteerd met een verandering in de vraag naar hun product. Eén van de uitgangspunten van ons model is dat grondstofproducenten over de tijd hun gehele voorraad verkopen. Indien gedurende een bepaalde periode de vraag naar hun product daalt, zullen ze de prijs ervan moeten verlagen. Hierdoor stijgt de vraag naar fossiele brandstoffen in tijden dat de emissielimiet geen rol meer speelt: in ons eenvoudige model daalt de vraag naar fossiele brandstoffen (en dus emissies) over de tijd zelfs zonder klimaatbeleid, waardoor op een gegeven moment de emissielimiet geen beperking meer is. Wanneer in deze tijd de vraag stijgt door de lagere prijs (uiteraard zonder dat emissies te hoog worden), zal over de tijd nog steeds de gehele voorraad worden verkocht. Deze verandering in de prijzen van de brandstoffen is dus een tweede prijs-effect, naast de prijs voor CO_2-emissies. Uiteraard heeft een prijsverlaging op korte termijn een veel kleiner effect op de vraag naar beide brandstoffen, en geen effect op de totale emissies: om ervoor te zorgen dat de totale hoeveelheid emissies niet groter wordt dan toegestaan, wordt de prijs van emissies verhoogd in reactie op de prijsverlaging. Op langere termijn, wanneer de voorraden dusdanig klein zijn dat emissies zelfs zonder beleid lager zijn dan de maximaal toegestane hoeveelheid, leidt de prijsverlaging wel tot extra vraag.

Het totale effect van de limiet op CO_2-emissies op de vraag naar de twee brandstoffen wordt dus bepaald door de relatieve CO_2-inhoud per eenheid energie van de twee brandstoffen, en de relatieve productiviteit per eenheid energie (die mede bepaald wordt door de relatieve voorraden). Doordat nu twee factoren een rol spelen bij het bepalen van de vraag naar de twee fossiele brandstoffen, hoeft het niet meer zo te zijn dat emissies per eenheid energie doorslaggevend zijn bij de beslissing van een producent van consumptiegoederen hoeveel van de twee brandstoffen te gebruiken. Het kan aantrekkelijk zijn om meer van de brandstof met de grotere hoeveelheid emissies per eenheid energie te gebruiken, indien het verschil in productiviteit per eenheid energie dusdanig groot is, dat dit het verschil in emissies meer dan compenseert. Cruciaal hierbij is de relatieve productiviteit die mede bepaald wordt door de relatieve schaarste. Het modelleren van de brandstoffen als niet-hernieuwbare hulpbronnen, wat bepaalt hoe schaars de brandstoffen zijn, speelt hierbij een grote rol.

Ons theoretische model geeft dus aan dat het in reactie op klimaatbeleid optimaal kan zijn om relatief minder van een schone, en relatief meer van een meer vervuilende brandstof te gaan gebruiken. Deze contra-inuïtieve uitkomst hebben we vervolgens getest met behulp van data voor de prijzen, extractie, en voorraden van fossiele brandstoffen. Hieruit blijkt dat het optimaal is om van 'smerige' kolen naar de minder vervuilende brandstoffen olie en gas te substitueren. De stijging in de gebruikersprijs van kolen, door de prijs voor CO_2-emissies, wordt dus niet gecompenseerd door de relatieve productiviteit van emissies van deze brandstof, en het is beter om relatief minder kolen te gaan gebruiken. Indien we echter olie en gas met elkaar vergelijken, dan volgt uit de empirische toepassing van ons theoretische model dat het optimaal is om van het schonere gas naar de meer vervuilende brandstof olie te substitueren. De productiviteit van CO_2 uit olie is dusdanig groot dat dit de hogere CO_2-prijs per eenheid energie (vanwege het hogere CO_2-gehalte) meer dan compenseert. Voor een zo groot mogelijke productie van consumptiegoederen, dient dus minder gebruik te worden gemaakt van kolen, ten gunste van olie en gas, maar dient het relatieve gebruik van olie toe te nemen ten opzichte van het schonere gas.

In hoofdstuk 2 wordt verder aangetoond dat dit effect groter is naar mate minder CO_2 uitgestoten mag worden, en dat het effect ook aanwezig is als we in plaats van een limiet op CO_2-emissies per jaar een limiet op de concentratie van CO_2 in de atmosfeer leggen. Een andere interessante uitkomst is dat als de limiet op de jaarlijkse CO_2-uitstoot een aantal jaren van tevoren wordt aangekondigd, het substitutie-effect nog steeds geldt voor de periode waarin emissies een prijs hebben. Echter, de substitutie in de periode tussen de aankondiging en uitvoering van het beleid is de andere kant op: van gas en olie naar kolen. Op deze manier houdt de economie meer van de meest productieve brandstof (productiviteit per eenheid emissies!) over voor de periode waarin emissies beprijsd worden.

De belangrijkste conclusie van hoofdstuk 2 is dus dat de introductie van schaarste en inter-temporele substitutie (door middel van het modelleren van fossiele brandstoffen als niet-hernieuwbare hulpbronnen) in de analyse van klimaatbeleid, de conclusies die komen uit statische modellen kan omdraaien. Ook de beperkte substitutie-mogelijkheiden spelen hierbij een rol, aangezien deze mede bepalend zijn voor de marginale productiviteit van de brandstoffen, en dus voor de richting van substitutie (van 'smerige' naar schonere brandstoffen, of juist andersom).

Hoofdstuk 3: Optimale extractie- en emissiepaden wanneer klimaatbeleid van tevoren wordt aangekondigd

Hoewel diverse vormen van overheidsbeleid kosten met zich meebrengen voor het bedrijfsleven, kunnen deze kosten verlaagd worden wanneer het beleid een aantal jaren van tevoren wordt aangekondigd. Zo hebben bedrijven een aantal jaren de tijd om zich voor te bereiden, bijvoorbeeld door middel van het aanpassen van productieprocessen.

Dit geldt ook voor klimaatbeleid. Klimaatbeleid legt een prijs op de emissies van CO_2, en leidt zodoende tot kosten voor bedrijven die veel energie gebruiken. Het Kyoto Protocol, dat bepaalt dat diverse westerse landen hun emissies moeten verlagen in de periode 2008-2012, werd al in 1997 ondertekend, en gaf bedrijven dus bijna 10 jaar de gelegenheid om zich voor te bereiden. Echter, in deze periode tussen het ondertekenen en het in werking treden van overheidsbeleid, zijn bedrijven en consumenten vrij om te doen wat ze willen. Voor klimaatbeleid betekent dit dat ze in deze periode vrij zijn in hun emissies van CO_2.

Wat betekent dit voor de emissies in deze periode? Hoe beïnvloedt het aankondigen van klimaatbeleid de prikkels voor de vraag naar en productie van fossiele brandstoffen, en dus emissies? Deze vragen staan centraal in hoofdstuk 3 van dit proefschrift.

In het vorige hoofdstuk kwam naar voren dat het feit dat fossiele brandstoffen niet-hernieuwbaar zijn, een grote rol kan spelen bij het effect van klimaatbeleid op de vraag naar fossiele brandstoffen en de daaraan verbonden emissies. In hoofdstuk 3 kijken we naar de vereenvoudigde situatie waarin productie plaats vindt op basis van slechts één niet-hernieuwbare hulpbron. We laten substitutie tussen brandstoffen dus buiten beschouwing, en kijken alleen naar het tijdspad van de vraag naar fossiele brandstoffen.

We kijken opnieuw naar een eeuwig-durende limiet op de jaarlijkse uitstoot van CO_2 ('Kyoto-voor-altijd'), maar deze wordt nu enige tijd van tevoren aangekondigd. Opnieuw geldt dat consumenten zoveel mogelijk willen consumeren, dat ze liever vandaag een euro hebben dan volgend jaar, maar ook dat de fossiele brandstof niet-hernieuwbaar is: wat we nu uit de grond halen en gebruiken, is niet meer beschikbaar voor de toekomst. Zoals aangegeven op pagina 163, betekent dit voor een gegeven voorraad fossiele brandstoffen dat het optimaal is om over de tijd steeds minder uit de grond te halen (consumenten hechten immers minder waarde aan consumptie in de toekomst dan aan consumptie in het heden). Dit betekent dat zonder klimaatbeleid emissies over de tijd dalen. Verder is het voor de eigenaren van de brandstof optimaal om over de tijd de totale voorraad op te maken.

Doordat klimaatbeleid van tevoren wordt aangekondigd, zijn er twee perioden waarin emissies niet beperkt worden door klimaatbeleid. Eerst is er een periode waarin het beleid wel is aangekondigd maar nog niet wordt uitgevoerd. De tweede periode is wanneer extractie zonder klimaatbeleid leidt tot minder emissies dan is toegestaan onder de emissielimiet. Deze tweede periode volgt dus op de periode waarin emissies gelijk zijn aan de maximaal toegestane hoeveelheid.

Gedurende de periode dat de overheid klimaatbeleid voert, mogen de emissies niet hoger zijn dan een bepaald niveau. Doordat we kijken naar het geval van slechts één niet-hernieuwbare hulpbron, betekent dit dat de extractie van deze hulpbron vast ligt gedurende de periode waarin de restrictie op emissies bindend is (er zijn geen andere productiefactoren in het model). Indien nu gedurende de periode waarin emissies vastliggen minder van hun product verkocht kan worden, moeten de eigenaren van de brandstof meer van hun product verkopen in andere perioden om over de tijd nog steeds hun gehele voorraad te verkopen. Ze zullen hun prijs dus moeten verlagen. De prijs van de brandstof groeit met de rentevoet, om brandstofeigenaren indifferent te laten zijn tussen het nu verkopen van hun product en de opbrengst op de bank zetten enerzijds, en het in de toekomst verkopen van hun product terwijl nu niks wordt verkocht anderzijds (zie pagina 163). Dit betekent dat in perioden waarin geen limiet ligt op de emissies van CO_2, de prijs van de brandstof gelijk is aan de prijs op het moment vlak na de aankondiging van het beleid, gecorrigeerd voor de jaarlijkse prijsstijging ter hoogte van de rentevoet. Doordat deze prijs lager is dan in het geval er nooit klimaatbeleid zou zijn, en een lagere prijs betekent dat de vraag hoger is, zijn in beide perioden waarin emissies niet beperkt worden door klimaatbeleid de emissies hoger in vergelijking met de situatie waarin nooit sprake zou zijn van klimaatbeleid. Oftewel: het aankondigen van een limiet op de CO_2-uitstoot leidt tot een toename van emissies in de periode tussen de aankondiging van het beleid en het moment waarop de limiet daadwerkelijk wordt afgedwongen. Dit effect treedt niet op in modellen waarin fossiele brandstoffen niet als niet-hernieuwbare hulpbron zijn gemodelleerd.

Deze toename van CO_2-uitstoot in de periode tussen aankondiging en uitvoering van klimaatbeleid gaat natuurlijk lijnrecht tegen het doel van klimaatbeleid in. Het doel is om de concentratie van broeikasgassen in de atmosfeer te stabiliseren. Het aankondigen van klimaatbeleid leidt echter tot een toename van emissies. Blijkbaar is er dus een afweging tussen het aankondigen van klimaatbeleid om de kosten ervan te verlagen enerzijds, en de effectiviteit van het beleid in termen van de CO_2-concentratie in de atmosfeer anderzijds.

Deel II: Klimaatbeleid, substitutie van productiefactoren, en technologische verandering

In hoofdstuk 4 en 5 van het proefschrift kijken we naar de relatie tussen klimaatbeleid, substitutiemogelijkheden, en technologische vooruitgang. Substitutie houdt in dat meer van een bepaalde productiefactor wordt gebruikt, en minder van een andere, zonder dat het productieniveau verandert. De substitutie-elasticiteit geeft aan hoe makkelijk dit kan: hoe hoger de substitutie-elasticiteit, hoe eenvoudiger het is om minder gebruik te maken van een productiefactor waarvan de kostprijs is gestegen (bijvoorbeeld door klimaatbeleid). Technologische vooruitgang houdt in dat meer geproduceerd kan worden bij gelijk gebleven gebruik van productiefactoren, doordat de productiviteit van één of meer factoren is toegenomen door nieuwe technologieën.

Hoofdstuk 4: Een nieuwe blik op 'carbon leakage': unilateraal klimaatbeleid met gerichte technologische vooruitgang

Wanneer een individueel land, of een groep landen die tezamen niet de gehele wereld omvat, besluit de emissies van CO_2 te verlagen (unilateraal klimaatbeleid), bestaat het gevaar dat andere landen hun emissies juist verhogen. Wanneer bijvoorbeeld de vraag naar fossiele brandstoffen in de regio met klimaatbeleid daalt, kan de wereldprijs van deze brandstoffen ook dalen. Als gevolg hiervan zullen andere landen juist meer fossiele brandstoffen gaan gebruiken. Tegelijkertijd zal de kostprijs van goederen die veel energie nodig hebben in hun productieproces stijgen in de landen met klimaatbeleid, vanwege de prijs voor CO_2-emissies, waardoor de vraag naar dit soort goederen zal verschuiven naar de landen zonder klimaatbeleid, omdat zij hun kostprijs niet hoeven te verhogen. Dit leidt tot extra productie in deze landen, en dus extra emissies. De toename in emissies in deze landen, in reactie op de emissieverlaging van andere landen, wordt 'carbon leakage' (letterlijk: koolstof lekkage) genoemd. Modellen waarin internationaal klimaatbeleid is gesimuleerd, suggereren dat 2% tot 41% van de emissiereductie in de landen met beleid teniet wordt gedaan door de stijging van emissies in andere landen.

In hoofdstuk 4 werpen we een nieuwe blik op carbon leakage, door te kijken naar de rol van technologische verandering bij unilateraal klimaatbeleid. Klimaatbeleid zorgt voor een verandering in de (relatieve) prijzen van meer en minder vervuilende producten door een prijs voor CO_2-emissies, waardoor ook de relatieve vraag naar deze producten verandert. Deze zelfde prijs- en vraagveranderingen hebben ook invloed op de richting van technologische verandering. Bedrijven in de sector die zorgt voor onderzoek en ontwikkeling (O&O) richten de ontwikkeling van nieuwe technologieën immers op sectoren waar voor hen de meeste winst te behalen valt. Indien nu de vraag naar producten van een bepaalde sector daalt, wordt het voor de O&O bedrijven minder interessant om technologieën te ontwikkelen voor deze sector.

In dit hoofdstuk kijken we naar twee landen die identiek zijn qua omvang en qua productietechnologieën. In beide landen bestaat de economie uit drie sectoren. Twee sectoren produceren intermediaire goederen die gebruikt worden voor de productie van een consumptiegoed in de derde sector. De twee sectoren voor intermediaire goederen verschillen in hun energie-intensiteit. Eén van de sectoren produceert intermediaire goederen die energie-extensief zijn, en de andere produceert intermediaire goederen die energie-intensief – en daarmee dus relatief ’vuil’ – zijn. Beide landen zijn ontwikkeld en doen aan O&O, maar slechts één van de twee landen voert klimaatbeleid (denk bijvoorbeeld aan Europa versus de Verenigde Staten). Beide landen moeten besluiten hoeveel arbeid (de enige productiefactor in het model) ze gebruiken voor de productie van schone producten, en hoeveel ze gebruiken voor de productie van energie, wat weer gebruikt wordt voor de productie van energie-intensieve goederen. Om de energie-extensieve en energie-intensieve intermediaire goederen te produceren wordt arbeid respectievelijk energie gecombineerd met machines. Technologische verandering houdt in dat nieuwe typen machines worden ontwikkeld. We kijken naar het effect van technologische verandering op emissies van het land zonder klimaat beleid (in reactie op een emissieverlaging in het andere land) en dan met name naar het geval waarin de sector die nieuwe technologiën ontwikkelt kan kiezen of ze dit doen voor de vervuilende sector of voor de schone sector. Daartoe ontwikkelen we twee varianten van ons model.

In de eerste variant kan de winstmaximaliserende O&O sector wel bepalen hoeveel ze investeren in nieuwe technologieën (nieuwe typen machines) in reactie op prijsveranderingen, maar niet voor welke sector deze technologie is. Dat wil zeggen, technologische verandering is wel endogeen (wordt bepaald binnen het model), maar de richting van de technologische verandering is exogeen (ligt vast). Voor deze variant van het model tonen we aan dat het land zonder klimaatbeleid inderdaad de emissies verhoogt in reactie op een emissieverlaging in het andere land. Doordat het land met beleid de emissies verlaagt, wordt de productie van energie-intensieve goederen in dit land duurder: er kan minder energie gebruikt worden om aan de emissielimiet te voldoen, dus moeten er meer machines ingezet worden om hetzelfde productieniveau te behalen. Omdat dit echter niet optimaal is (wanneer bedrijven vrij zijn in hun productiekeuzes kiezen ze immers voor meer energie en minder machines), zijn de kosten per product echter hoger. In het andere land is dit niet het geval, en dus wordt het aantrekkelijk om vervuilende goederen uit het andere land te importeren, waardoor de emissies in dat land toenemen. Echter, de (marginale) productiviteit van productiefactoren daalt naar mate er meer van wordt gebruikt: als je steeds meer arbeid gebruikt om energie te produceren stijgt de productie van energie wel, maar neemt de energieproductie per arbeider af. Hierdoor wordt ook de kostprijs in het andere land hoger. De productie van energie en energie-intensieve goederen in het land zonder klimaatbeleid neemt toe, totdat de prijzen voor beide landen weer gelijk zijn: doordat er vrije handel is tussen de landen, moeten de prijzen uiteindelijk weer gelijk zijn. Als gevolg hiervan nemen de emissies in het land zonder beleid wel toe, maar met een kleinere hoeveelheid dan de emissiedaling in het andere land. De wereldwijde emissies nemen dus wel af, maar met minder dan de emissiedaling in het land met klimaatbeleid, ondanks dat bedrijven in deze variant van het model zelf kunnen bepalen hoeveel ze investeren in onderzoek en ontwikkeling.

In de tweede variant van het model kijken we naar het geval waarbij bedrijven in de sector voor onderzoek en ontwikkeling wél kunnen bepalen voor welke sector (de schone of de vervuilende) ze nieuwe machines ontwikkelen. We zijn dus met name geïnteresseerd in het effect van gerichte technologische verandering - het feit dat de O&O sector kan bepalen voor welke sector ze nieuwe machines ontwikkelen - op de emissies van het land zonder klimaatbeleid. Het is voor de O&O sector enerzijds aantrekkelijk om nieuwe technologieën te ontwikkelen voor de sector waar de prijs van het intermediaire goed het hoogst is, maar anderzijds ook om nieuwe technologieën te ontwikkelen voor de sector die de meeste producten verkoopt. Klimaatbeleid in een land verlaagt de productie van energie in dat land, waardoor klimaatbeleid een negatief hoeveelheidseffect op O&O voor de energie-intensieve sector heeft. Tegelijkertijd leidt een lager aanbod tot een hogere prijs voor producten in de vervuilende industrie en dat heeft een positief prijs-effect op O&O voor deze sector. De vraag is nu welk effect sterker is, en hoe dit doorwerkt in de emissies van het land zonder klimaatbeleid.

Het effect op technologische verandering en op emissies hangt af van de mogelijkheden voor producenten van consumptiegoederen om tussen de twee soorten intermediaire goederen te substitueren. Dat wil zeggen: hoe makkelijk is het om minder van het energie-intensieve goed te gebruiken en meer van het schonere, in reactie op een verandering in de relatieve prijs van de intermediaire goederen, en toch evenveel van het consumptiegoed te produceren? Indien het relatief makkelijk is om tussen beide goederen te substitueren, zal een prijsverandering door klimaatbeleid leiden tot een grote vraagverandering in de richting van het schonere product. Dit betekent dat het bovengenoemde hoeveelheidseffect groter is dan het prijs-effect, en dat in reactie op klimaatbeleid de O&O sector in beide landen (de goederen zijn immers vrij verhandelbaar tussen de twee landen) nieuwe technologieën gaat ontwikkelen voor de energie-extensieve, schone, sector. Indien het daarentegen moeilijk is om van het ene intermediaire goed naar het andere te substitueren, zal de vraagverandering die volgt op een prijsverandering relatief klein zijn. In dat geval is het prijseffect groter, en zullen nieuwe technologieën voor de vervuilende sector ontwikkeld worden.

Hoe deze verandering in technologieniveaus voor de twee sectoren vervolgens van invloed is op de relatieve productiviteit van arbeid in de schone sector ten opzichte van energie in de energie-intensieve sector, hangt eveneens af van de substitutiemogelijkheden. Het netto-effect is dat technologische verandering gericht is op het vergroten van de relatieve productiviteit van de productiefactor die relatief groter in omvang wordt. In ons geval is dat dus arbeid in de relatief schone industrie: het land met klimaatbeleid kan minder energie produceren, waardoor het wereldaanbod van energie daalt, en het relatieve aanbod van arbeid en van energie-extensieve goederen stijgt. Doordat zowel het relatieve aanbod als de relatieve productiviteit (en dus de beloning voor arbeid in de energie-extensieve sector) toeneemt, neemt het kostenaandeel van energie in de totale (wereld-)productiekosten af. Technologische verandering is zodoende ’energie-besparend’.

Doordat de relatieve productiviteit van energie daalt als gevolg van de technologische verandering (door de stijging in de productiviteit van arbeid in de andere sector), wordt het voor het land zonder klimaatbeleid minder aantrekkelijk om energie in te zetten en energie-intensieve goederen te produceren. Het gevolg hiervan is dat dit land, in vergelijking met de situatie waarin technologische verandering niet op een bepaalde sector gericht kon worden, minder energie zal produceren en dus minder CO_2 zal uitstoten. Dat wil zeggen, doordat de O&O sector haar innovaties kan richten op de sector waar deze de meeste winst opleveren, is de mate van carbon leakage ondubbelzinnig lager. In het specifieke geval waarin de substitutie-elasticiteit precies gelijk is aan één, wordt de mate van carbon leakage echter niet beïnvloed door de richting van technologische verandering.

De volgende vraag is: kan de daling in de relatieve productiviteit van energie, door gerichte technologische verandering, zo groot zijn dat het voor het land zonder klimaatbeleid aantrekkelijk wordt om de emissies, in reactie op de emissiedaling in het andere land, ook te verlagen? In dat geval zou sprake zijn van ’negatieve carbon leakage’: in plaats van een toename in de emissies van het land zonder klimaatbeleid, zouden in dat geval de emissies in dat land ook dalen. Of dit wel of niet mogelijk is, hangt af van de mogelijkheden tot substitutie tussen de twee intermediaire goederen, welke nauw samen hangen met de prijselasticiteit van de relatieve vraag naar energie (ten opzichte van de vraag naar arbeid in de andere sector). Het blijkt dat als deze prijselasticiteit groot genoeg is (om precies te zijn: groter dan 2), dat in ons model het land zonder klimaatbeleid inderdaad de emissies vrijwillig zal verlagen, door de relatieve daling in de productiviteit van energie als gevolg van technologische verandering. Een blik op de literatuur waarin prijselasticiteiten voor energie worden geschat op basis van data, leert ons dat een waarde groter dan 2 niet onwaarschijnlijk is.

Wat betekenen deze conclusies voor klimaatbeleid? In de numerieke modellen die de gevolgen van unilateraal klimaatbeleid (zoals bijvoorbeeld het Kyoto Protocol) doorrekenen, wordt geen rekening gehouden met het feit dat prijsveranderingen invloed hebben op innovatie en dus op de richting van technologische verandering. Wij hebben aangetoond dat wanneer deze modellen daar wel rekening mee zouden houden, deze lagere waarden voor carbon leakage zouden kunnen vinden dan tot nu toe. Dit kan vervolgens invloed hebben op het politieke debat: één van de redenen waarom de Verenigde Staten het Kyoto Protocol niet geratificeerd hebben, was de angst dat een emissieverlaging in de VS zal leiden tot een toename in de emissies in landen buiten het Protocol, zoals bijvoorbeeld China. Wanneer kwantitatieve modellen die carbon leakage bestuderen rekening houden met endogene, gerichte technologische verandering, vinden zij wellicht dat de mate van carbon leakage minder groot is dan tot nu toe gedacht.

Hoofdstuk 5: Productiefuncties voor het modelleren van klimaatbeleid: een empirische analyse

In de recente literatuur rond de effecten van klimaatbeleid speelt technologische verandering een grote rol. Met behulp van numerieke modellen proberen economen uit te zoeken hoe klimaatbeleid invloed heeft op technologische verandering, en hoe dit vervolgens weer andere variabelen beïnvloedt. Tot enkele jaren geleden werd in dit soort modellen de stand van de techniek constant gehouden. Na de opkomst van de literatuur over endogene technologische verandering zijn ook economische modelbouwers voor klimaatbeleid begonnen hun numerieke modellen aan te passen om technologische verandering te modelleren als een endogeen proces, dat wil zeggen gericht op winstmaximalisatie en reagerend op prijs- en hoeveelheidsveranderingen.

Een probleem in deze literatuur is echter dat de precieze formulering van de productiefuncties in deze modellen in het algemeen niet gebaseerd is op empirische analyses. Een productiefunctie geeft aan hoe de inzet van productiefactoren zoals arbeid, kapitaal en energie leidt tot de productie van eindproducten: hoe makkelijk is het om meer van de ene productiefactor te gebruiken en minder van de ander bij gelijkblijvend productieniveau, en met hoeveel neemt het productieniveau toe indien de inzet van een productiefactor met x% toeneemt? De productiefuncties van modellen die klimaatbeleid simuleren bestaan veelal uit functies met constante substitutie-elasticiteiten (CES - constant elasticity of substitution) met als productiefactoren kapitaal, arbeid, en energie. De productiefuncties die gebruikt worden in de numerieke modellen in deze literatuur verschillen in drie dimensies.

Ten eerste verschillen de modellen in de zogenaamde nesting-structuur van de productiefunctie. Wanneer er drie productiefactoren zijn, kunnen deze op verschillende manieren gecombineerd worden. Kapitaal en arbeid kunnen eerst gecombineerd ('genest') worden in één CES functie, om dit kapitaal-arbeid aggregaat daarna te combineren met energie in een nieuwe CES functie. Maar het is ook mogelijk om eerst kapitaal en energie te combineren, en dit aggregaat te combineren met arbeid in een tweede CES functie. Ten derde is het mogelijk om arbeid en energie eerst te combineren in één CES functie. Ten slotte kunnen alledrie productiefactoren samen in één CES functie gecombineerd worden, in welk geval er geen sprake is van nesting. De keuze van de nesting-structuur is van invloed op het antwoord op de vraag hoe makkelijk minder van de ene factor gebruik gemaakt kan worden, en meer van de ander, in reactie op prijsveranderingen.

Ten tweede verschillen de modellen in de hoogte van de gebruikte substitutie-elasticiteiten, zelfs wanneer ze dezelfde nesting-structuur gebruiken. Een belangrijke rol is hierbij weggelegd voor de substitutie-elasticiteit (die in het vorige hoofdstuk, in een productiefunctie met andere productiefactoren, ook een belangrijke rol speelde). Hoe hoger de substitutie-elasticiteit, hoe makkelijker het is om minder gebruik te maken van een factor waarvan de prijs is gestegen. En dus ook: hoe lager de kosten voor de economie zijn als de prijs van energie (bijvoorbeeld als gevolg van klimaatbeleid) wordt verhoogd.

Ten slotte speelt de manier waarop technologische verandering van invloed is op de relatieve productiviteit van de drie productiefactoren een grote rol. Zoals in het vorige hoofdstuk is aangetoond, kan de 'gerichtheid' van technologische vooruitgang grote invloed hebben op economische uitkomsten (in het vorige hoofdstuk op de emissies van het land zonder klimaatbeleid). Indien de prijs van een productiefactor verandert, willen producenten nieuwe technologieën op dusdanige wijze inzetten dat de productiviteit van hun productiefactoren zoveel mogelijk toe neemt. In het vorige hoofdstuk is aangetoond dat producenten flexibeler zijn wanneer zij nieuwe technologieën kunnen richten op een bepaalde sector of productiefactor: zij kiezen dan immers voor een ander pad van technologische verandering (namelijk gericht op het vergroten van de relatieve productiviteit van de factor die relatief in omvang toe neemt) dan in het geval waarin dit pad vast ligt. In de literatuur over klimaatbeleid verschillen modellen in de mate waarin dit mogelijk is: in sommige modellen kunnen nieuwe technologieën gericht worden op iedere productiefactor, in sommige modellen alleen op energie, en in andere modellen kan alleen het algemene niveau van technologie beïnvloed worden, net als bij de niet-gerichte technologische verandering in het vorige hoofdstuk.

Een groot probleem van deze literatuur is dat de auteurs hun keuze voor hun productiefunctie niet baseren op empirische studies. Met behulp van data over productieniveaus en over het gebruik van kapitaal, arbeid, en energie, en over hun prijzen, kan bepaald worden hoe de drie productiefactoren samen hangen. In hoofdstuk 5 van het proefschrift wordt dit voor de eerste keer op systematische wijze gedaan.

Met behulp van data voor 7 sectoren in 12 OECD landen uit de periode 1978-1996 worden drie stelsels van vergelijkingen geschat, voor iedere nesting structuur één (eerst kapitaal en arbeid, of eerst kapitaal en energie, of eerst energie en arbeid; vervolgens kan binnen iedere structuur getest worden of de drie factoren niet net zo goed alledrie in één CES functie geplaatst kunnen worden). De uitkomsten van de schattingen geven aan (1) welke nesting-structuur het beste bij de data past; (2) hoe groot de substitutie-elasticiteiten dienen te zijn volgens de data; (3) of de technologie-trends van de drie productiefactoren over de tijd verschilden of niet.

Een eerste conclusie is dat volgens de data kapitaal eerst met arbeid gecombineerd dient te worden. Echter, uit statistische tests blijkt dat voor diverse sectoren en diverse landen de drie factoren net zo goed in één CES functie geplaatst kunnen worden. Als we vervolgens kijken hoe numerieke modellen in de literatuur voor klimaatbeleid gespecificeerd zijn, dan blijkt dat de meeste modellen ook voor één van deze twee nesting-structuren gekozen hebben.

Onze tweede conclusie is echter dat de waarden die wij vinden voor de substitutie-elasticiteit voor kapitaal en arbeid, en die voor de substitutie-elasticiteit voor het kapitaal-arbeid aggregaat en energie, significant lager zijn dan de waarden die sommige modellen in de literatuur gebruiken. Voor beide elasticiteiten vinden wij waarden ongeveer tussen 0,2 en 0,6. Statistische tests tonen aan dat een waarde van één te hoog is. Echter, diverse modellen gebruiken een waarde van één.

Ten derde tonen wij aan dat de technologie-trends voor de drie productiefactoren sterk verschillen. Dit betekent dat technologische ontwikkeling in werkelijkheid gericht kan worden op de individuele productiefactoren, zodat de relatieve productiviteit van iedere productiefactor gestuurd kan worden. Modellen die hier niet in voorzien, of die alleen toestaan dat de productiviteit van energie kan worden beïnvloed door technologische verandering, missen dus een belangrijk verband met de realiteit.

Wat betekent dit alles voor de uitkomsten van de modellen, wanneer deze de invoering van klimaatbeleid simuleren? Ten eerste is het gebruik van een te hoge substitutie-elasticiteit van invloed op de uitkomsten van het model zonder gerichte technologische vooruitgang (het referentiepunt waartegen de resultaten van het model met gerichte technologische verandering worden afgezet). Ten tweede leidt een te hoge substitutie-elasticiteit er toe dat er in het model minder druk is om te investeren in nieuwe technologieën. Bij een hoge elasticiteit is het immers eenvoudiger om weg te substitueren van de factor waarvan de prijs is gestegen. Modellen met een te hoge elasticiteit onderschatten dus de rol van endogene en gerichte technologische verandering in het bepalen van de kosten van klimaatbeleid.

Ten derde negeren modellen die gebruik maken van een substitutie-elasticiteit die gelijk is aan één de rol van de richting van technologische verandering. In dat geval is de CES productiefunctie een Cobb-Douglas productiefunctie, waarin factorspecifieke technologische verandering geen invloed heeft op de relatieve productiviteit van productiefactoren. Bij een lagere elasticiteit kan technologische verandering specifiek gericht worden op bepaalde factoren, en kan een gewenste verandering in de relatieve productiviteit van de factoren wellicht worden bereikt tegen lagere kosten voor onderzoek en ontwikkeling.

Hoe groot deze effecten van een andere productiestructuur en een lagere substitutie-elasticiteit daadwerkelijk zijn, kan alleen worden gevonden door de modellen uit de literatuur daadwerkelijk aan te passen en de nieuwe uitkomsten te vergelijken met de oude.