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Flexible Climate Policy Mechanisms and Induced Technical Change

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To Kaisa

And to my parents

Overview

Table of Contents

List of Abbreviations

AAU	Assigned Amount Units
AEEI	Autonomous Energy Efficiency Index
BAU	Business As Usual
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
COP	Conference of the Parties
ENB	Earth Negotiation Bulletin
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GtC	Gigatons of Carbon
IIASA	International Institute for Applied System Analysis
INC	Intergovernmental Negotiating Committee
IPC	Innovation Possibility Curve
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
KyDyn	Kyoto Dynamic Case
KyEv	Kyoto Forever Case
LULUCF	Land Use, Land Use Change and Forestry
OECD	Organization for Economic Co-Operation and Development
ppm	parts per million of volume
R&D	Research and Development
SBI	Subsidiary Body for Implementation
SBSTA	Subsidiary Body for Scientific and Technological Advice
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environmental Programme
WMO	World Meteorological Organization
WSSD	World Summit for Sustainable Development

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Preface

Sowohl in der ökonomischen Literatur zum Klimaschutz als auch in der aktuellen politischen Debatte spielt die Suche nach kostengünstigen Ansätzen des Klimaschutzes eine überragende Rolle. Diese schlägt sich unter anderem in den sogenannten Flexibilitätsmechanismen des Kyoto-Protokolls zum Klimaschutz nieder, zu denen auch ein länderübergreifender Emissionsrechtehandel gehört. Andererseits wird diesem Instrument vielfach entgegen gehalten, dass in Ländern mit hohem Emissionsaufkommen die Möglichkeit, Emissionsrechte zu erwerben, den Anreiz senkt, den technischen Fortschritt in Richtung emissionsärmerer Technologie voran zu treiben.

Diese Debatte bildet den Hintergrund des vorliegenden Buches. Die Fragestellung lautet: Welche Auswirkungen hat eine Einschränkung des internationalen Handels mit Emissionsrechten für Klimagase auf den emissionsmindernden technischen Fortschritt sowie die gesamtwirtschaftliche Wohlfahrt der einzelnen Weltregionen?

Zur Analyse dieser Fragen nutzt der Verfasser ein numerisches klimaökonomisches Modell und entwickelt dieses weiter, so dass CO_2-sparender technischer Fortschritt endogen auf ökonomische Anreize reagiert. Auf Grundlage des modifizierten Modells führt der Verfasser Szenarienrechnungen durch. Zu den wesentlichen Ergebnissen gehört die qualitativ unterschiedliche Auswirkung von Beschränkungen des Emissionshandels auf Anbieter und Nachfrager von Emissionsrechten. Während der technische Fortschritt bei den Nachfragern angekurbelt wird – was den Erwartungen der Verfechter von Handelsbeschränkungen entspricht – wird er bei den Anbietern reduziert. Die *globale* Wohlfahrt wird durch den zulässigen Grad an Emissionshandel wenig beeinträchtigt. Allerdings werden die *regionalen* Wohlfahrten in den Käuferregionen von Emissionsrechten tendenziell negativ von Handelsbeschränkungen berührt, während die Verkäuferregionen geringfügig profitieren. Bei der Frage nach der Sinnhaftigkeit solcher Beschränkungen geht es also weniger um globale Effizient als um ein Problem internationaler Verteilung.

Das vorliegende Buch beschäftigt sich mit einer sehr wichtigen und aktuellen Fragestellung und kommt zu sehr interessanten und potentiell relevanten

Ergebnissen. Es leistet einen wichtigen Beitrag in der Debatte um eine sachgerechte und problemorientierte Klimaschutzpolitik.

Prof. Dr. Heinz Welsch

Part I
The Problem

1 Introduction

Climate change due to anthropogenic carbon emissions has been a source of growing concern within the last decades. In environmental-economic research a great deal of effort has been devoted to estimating the costs and benefits of carbon abatement policies. In addition, the search for strategies to reach carbon abatement targets at low cost has been an important research topic and a hot issue in international climate negotiations.

Carbon abatement is a purely global common. That is, the geographical distribution of carbon emissions and abatement do not matter, only the amount and timing is important. This feature creates a benchmark for the so-called economic, or market-based instruments of environmental protection. In such a case, the standard economic reasoning suggests that overall costs are minimized when abatement is allocated among parties in such a way as to equalize marginal abatement costs. Such an allocation can be sustained by market-based mechanisms. Hence, the 'standard-economic' conclusion is that market-based instruments indeed lower the total cost of achieving a given overall abatement target, by enhancing an equalization of marginal abatement costs across parties.

This line of reasoning has played a key role in international climate diplomacy. One of the outcomes of the climate negotiations under the United Nations Framework Convention on Climate Change is the Kyoto Protocol. For the first time in history, a group of signatory countries, the so-called Annex B countries of the Kyoto Protocol, obligated themselves to quantitative emission limits. An important ingredient to the Kyoto Protocol is the introduction of so-called flexibility mechanisms that resemble the spirit of the market-based instruments. This enables the (industrialized) countries to reduce carbon emissions where and how it is cheapest.

In spite of their presumed benefits, the flexible Kyoto mechanisms are much debated. One argument is that they prevent countries from investing in technological progress. Placing restrictions on flexibility is claimed to imply long-term benefits due to induced technological change. In the political arena, this and related reasoning has motivated demands that ceilings should be imposed on the degree to which emissions are tradable. Analytically, this calls for an analysis of the interrelations between technical change and the degree of flexibility of the Kyoto mechanisms.

The current work examines the implications of ceilings on emissions trading in climate policy when there is induced carbon-saving technical change. To that purpose the well-known RICE-99 integrated assessment model of Nordhaus and Boyer (2000) is extended by endogenizing technical change that is directed towards energy productivity, hence, the ‘de-carbonization’ of production hitherto included in RICE-99 in an exogenous fashion. More specifically, a stock of knowledge, that raises the productivity of carbon energy in terms of the energy services that can be derived from it, is introduced into the model. The knowledge stock can be augmented by cumulative R&D spending, The result is a model that contains emissions trading as well as endogenous technical change. The model extended in this way is used to simulate several variants of carbon abatement scenarios considered in the previous literature. These abatement scenarios are combined with different assumptions on the admissible degree of emissions trading.

There have been earlier approaches at endogenizing technological progress in economic models of climate change, but only few attempts to analyze the linkage between the flexibility mechanisms and induced technological change. To my knowledge only Buonanno et al. (2000a, 2001a) have so far analyzed restrictions to emissions trading in the presence of induced technological progress. However, they use the old version of the RICE model of Nordhaus and Young (1996). In that version of RICE, energy is not portrayed explicitly, neither as a production input nor as a source of carbon emissions. Rather, there is a ‘reduced form’ representation of production and emissions, the latter being proportional to output. Using RICE-99 as the basis for modeling allows to focus on that category of technological progress – de-carbonization – which is most likely to respond to the rationing of carbon emissions.

The current work is structured as follows. After an introduction to the international climate regime (chapter 2) and some basic concepts concerning the analysis of technical change (chapter 3), current innovation theories (chapter 4) and their application in modeling endogenous growth (chapter 5) are reviewed. Chapter 6 investigates the application of endogenous growth to modeling climate change policy. Chapter 7 describes the new RICE-99 model in some more detail. Chapter 8 describes my own modeling approach and the calibration procedure whereas chapter 9 shows the scenarios and simulations. Chapter 10 summarizes and concludes.

2 International Climate Policy and Technology

2.1 Introduction

This chapter sets the stage. It explains the motivation and background to the present modeling effort. Section 2.2 gives a short overview of the international climate change regime with a focus on the Kyoto Protocol and its flexibility mechanisms. Section 2.3 highlights the problems of current presentations of technology in climate change policy modeling and section 2.4 extends these problems to the flexibility mechanisms that gave rise to the present work.

2.2 Climate Diplomacy

2.2.1 Scientific Evidence: IPCC

The natural greenhouse effect enables life on earth as we know it today. The sun's radiation, that is reflected from the earth's surface and trapped by atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHGs), raises the global mean temperature to about 15 degrees Celsius. By burning fossil fuels, however, additional CO_2 is released into the atmosphere. Most scientist believe that the amount of the additional anthropogenic CO_2, that has been released since the beginning of the industrialization, has altered the natural greenhouse effect, called "global warming".

The increasing scientific evidence about global climate change led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 by the United Nations Environmental Programme (UNEP) and the World Meteorological Organization (WMO). The IPCC has so far issued three assessment reports and summaries for policy makers (IPCC 1990, 1995, 2001). These reports are divided into three main parts that are drafted by three respective working groups, namely the science of climate change (working group I), impacts, adaptation and mitigation of climate change (working group II) and economic and social dimension of climate change (working group III). (Grubb et al. 1999, p. 4; Oberthür and Ott 1999, pp. 3-4; ENB[1] 1995, p. 1).

Drafted and reviewed by hundreds of experts from all over the world the assessment reports reflect the state of knowledge on climate change and provide the scientific input for the international climate negotiating process. The summaries for policy makers, however, are negotiated with state representatives, that is, their wording is also subject to political interests. (Grubb et al. 1999, p. 4; Oberthür and Ott 1999, pp. 3-4; ENB 1995, p. 1). In addition, the IPCC has also issued special reports on specific issues such as emissions scenarios (IPCC 2000a) or technology transfer (IPCC 2000b) as well as technical papers, for instance on technology policies for mitigating climate change (IPCC 1996).[2]

The IPCC states that the risk of climate change damages would be reduced by stabilizing the atmospheric concentration of CO_2. A lower concentration would lesson the increase in global mean temperature and fewer associated damages such as sea level rise, catastrophic events and the extinction of species. Stabilizing the atmospheric concentration of CO_2 at 550 parts per million of volume (ppm) – approximately twice the pre-industrial level – would require today's worldwide CO_2 emissions to drop below the levels of 1990 in the second half of this century, decrease further *by* 70% below 1990-level by the middle of the next century and continue to decrease to even lower levels. (IPCC 2001, p. 99, 103).

Stabilization at 500 ppm is an 'often discussed number' because it would yield another safety margin and is believed to cause climate damages that can be coped with. This, in turn, would imply grater reductions. Furthermore, acknowledging that less developed countries have a right to development would imply even greater reductions for the developed world.

2.2.2 Framework Convention on Climate Change

Following a mandate from the United Nations' General Assembly, and supported by UNEP and the WMO, the preparations of the Intergovernmental Negotiating Committee (INC) led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. The same

1 See www.iisd.ca/linkages/vol12/ for the archive of the Earth Negotiation Bulletin (ENB) covering the whole diplomatic process.

2 See www.ipcc.ch/ for an overview on the IPCC's publications

year the convention was opened for signature at the UN Conference on the Environment and Development (the so-called Earth Summit) in Rio and entered into force in 1994. (Grubb et al. 1999, p. 36; Oberthür and Ott 1999, p. 33; ENB 1995, p. 2; UNEP and UNFCCC 2001, sheet 17.2).

The UNFCCC's ultimate objective is described in Article 2 as the "stabilization of greenhouse gas [GHG] concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Article 3 states "common but differentiates responsibilities" of the signatory countries and Article 4 lists the signatories' commitments such as the establishment and reporting procedure of national inventories of GHG's and promotion of sustainable development. (Grubb et al. 1999, p. 36-43; Oberthür and Ott 1999, pp. 33-9).

The agreement on the commitments was – and still is – one of the most controversial issues. Therefore, the convention does not specify any *legally binding* target or timetable for any country. Only a non-binding obligation is put on the countries listed in Annex I of the convention that these Parties shall adopt national policies to mitigate climate change and take the lead in changing long-term emission trends (Article 4.2). (ENB 1997, p. 1; Oberthür and Ott 1999, pp. 35, 47). Annex I comprises mainly the OECD-countries and the Central and Eastern European countries with economies in transition.

The subsequent articles of the UNFCCC establish the institutions and mechanisms to run the convention and the diplomatic process. The Conference of Parties (COP, Article 7) is the supreme decision-making body of the regime and usually meets annually. The Subsidiary Body for Scientific and technological advice (SBSTA, Article 9) and the Subsidiary Body for Implementation (SBI, Article 10) work under the COP's guidance and usually meet twice per year. Furthermore, a secretariat and a financial mechanism were established (Article 8, 11). (Grubb et al. 1999, p. 36-43; Oberthür and Ott 1999, pp. 33-9). The SBSTA and SBI cover a broad range of issues. Therefore, they might establish working groups on specific issues, for instance the Expert Group on Technology Transfer (ENB 2003).

2.2.3 Negotiations prior to and after the Kyoto Protocol

Due to the lack of binding quantitative commitments, the First Conference of the Parties (COP-1), held in 1995 in Berlin, Germany, decided that a legally binding instrument containing quantitative emissions reductions would be necessary. This decision was called the Berlin Mandate and involved the establishment of a so-called Ad Hoc Group on the Berlin Mandate. This group led the negotiating process that culminated in the agreement to a protocol to the UNFCCC at COP-3 in Kyoto, Japan in 1997. (ENB 1997, p. 1-2; Oberthür and Ott 1999, pp. 35, 47).

The agreement on the Kyoto Protocol left many questions unresolved. Grubb et al. (1999, p. 248) point out that "Most countries needed several months even to start understanding what had been agreed at Kyoto… a lot of questions with few clear answers." Even though the Kyoto Protocol established legally binding quantitative limits on emissions of GHG's, there were no decision on a number of rules and operational details (ENB 2002a, p. 2).

The necessity to agree on these missing rules and operational details – later referred to as 'Kyoto's unfinished business' – prior to the ratification of the protocol led to the establishment of an extensive work program at COP-4 in Buenos Aires in 1998. This work program, called 'Buenos Aires Plan of Action', set a schedule for agreement on the necessary issues so that the protocol could be agreed upon at COP-6. These issue where protocol-related such as the flexibility mechanisms or accounting methods for emissions reductions as well as convention-related issues such as the transfer of technologies. (Grubb et al. 1999, pp. 248-9; ENB 2002a, p. 2).

At COP-6 in The Hague, the Netherlands in 2000 key issues concerning the flexibility mechanisms and the financial mechanisms were still unresolved due to opposing positions of the EU and the US. Delegates could not reach an agreement and postponed the conference. In March 2001, the US administration stated it would not ratify the Kyoto Protocol. At the resumed COP-6 in Bonn, Germany in July 2001 delegates could reach an agreement on most issues, later coined the 'Bonn Agreements'. However, the agreement was not complete so that all draft decisions were forwarded to COP-7. Using the Bonn Agreement as the basis, COP-7 in Marrakech, Morocco in fall 2001 finally brought three years of negotiation under the Buenos Aires Plan of Action to a close. The decisions of COP-7 were coined the 'Marrakech Accords' (ENB 2002a) or 'Bonn Marrakech Accords'.

The World Summit for Sustainable Development (WSSD) in 2002 in Johannesburg, South Africa produced a 'Plan of Implementation' in which the UNFCCC's ultimate objective (see section 2.2.2) is reaffirmed and parties are urged to ratify the Kyoto Protocol. The Plan of Implementation emphasized the importance of cleaner energy technologies. (ENB 2002a, p. 2; ENB 2002b, p. 9).

2.2.4 Kyoto Protocol

Oberthür and Ott (1999, p. 95) call the Kyoto Protocol "one of the most ambitious treaties ever adopted". For the first time an international environmental treaty contains legally binding quantitative emissions targets and timetables differentiated by countries (Article 3). The overall commitment is to reduce GHG emissions by at least 5% with respect to the emission levels of 1990. Parties have to comply until the start of the first commitment period, that lasts from 2008-2012. The differentiated targets for the countries are listed in Annex B of the protocol. Annex B mostly resembles the Annex I parties of the convention as mentioned in section 2.2.2.

In addition to CO_2, the other GHG's CH_4, N_2O, hydrofluorocarbons (HFC's), Perfluorocarbons (PFC's) and sulphur hexafluoride (SF_6), called the 'six gas basket' are covered as well and are listed in Annex A of the protocol. These gases are converted by their 'global warming potential' into CO_2-equivalents.

Another novelty in international environmental legislation is the introduction of the so-called flexibility mechanisms, that primarily aim at reducing costs. The rules and operational details of these mechanisms were not agreed upon at COP-3 and constitute Kyoto's unfinished business. Due to these omissions, Oberthür and Ott (1999, p. 95) call the Kyoto Protocol "one of the most ambiguous legal instruments" as well. The mechanisms are Joint Fulfillment, known as 'bubbling' (Article 4), Joint implementation (JI, Article 6), the Clean Development Mechanism (CDM, Article 12) and Emissions Trading (Article 17). The latter three are also known as the so-called Kyoto Mechanisms.

The Kyoto Mechanisms are among the most contentious issues that led to the failure of COP-6 and some of them could not even be agreed upon at COP-6 Part II. Therefore, all draft decisions were forwarded to COP-7 where they could be resolved in a 'package deal'. (ENB 2001a, p. 6-7; ENB 2001b, p. 6).

2.2.4.1 Emissions Trading

Emissions trading is considered as the flexibility mechanism with the greatest potential. It was of great importance for the OECD countries outside the EU as well as for Russia. (Oberthür and Ott 1999, pp. 187, 194). The concept of emissions trading has long been promoted by environmental economist as a market oriented instrument with superior properties as compared to the so-called command-and-control legislation. It has been implemented on a national scale in the US with regard to sulphur dioxide (cp. e.g. Hansjürgens 1998).

Emissions trading, or cap and trade, aims at minimizing compliance cost by reducing emissions where it is cheapest. Each party is granted a certain amount of emissions. These emissions limits, or Assigned Amount Units (AAUs), constitute a commodity if they are tradable and below the actual emissions thus implying scarcity. If actual emissions in a country are higher than the assigned amounts, the country may choose to buy additional permits from other countries whose actual emissions are below their assigned amounts. Alternatively, it may reduce emissions domestically as far as necessary or it may reduce more than necessary and sell the assigned amounts that exceed actual emissions. If domestic abatement costs exceed the market price of the internationally traded emission rights, it is rational to buy permits and vice versa. Therefore abatement takes place where it is cheapest[3].

In order to prevent parties from over-selling and therefore not being able to comply, parties are required to hold a so-called commitment reserve during the commitment period. The commitment reserve either consist of 90 percent of the parties' AAUs or five times their most recent inventory, whichever is lowest. (UNFCCC 2003b).

One of the most controversial issues was the issue of supplementarity, that is, to which extent the mechanisms could be used for compliance. The EU took the position that emissions trading should be supplemental to domestic action so that compliance involves a 'real' abatement effort. Therefore, the EU proposed to limit emissions trading so that a minimum 50% of total abatement has to be reached by domestic action. The US, Canada and Australia (members of the so-called umbrella group) rejected the notion of supplementarity because they feared too high compliance cost. (Oberthür and Ott 1999, pp. 197-201).

One of the main reasons to limit emissions trading is the so-called hot-air problem. The emission reduction commitments are calculated with respect to the emission levels of 1990. This was right before the collapse of emissions in the former Soviet Union due to the aftermath of the transition from a cen-

3 See, for instance, Endres and Querner (2000) or any other environmental economic textbook.

trally planned economy to a market economy. Since the actual emissions of these countries – mainly Russia and the Ukraine – are much lower than their assigned amounts, they have large amounts of excess emission for sale. These excess emission rights are called hot air because they are available without any real abatement effort. As a result, the collective Kyoto target had in fact already been reached the year after it was signed (Grubb et al. 2001, p. 21).

Full emissions trading would make the hot air accessible to all other countries where Russia and the Ukraine would act as the main supplier and the US would have been the largest buyer of permits. Therefore, the countries could comply with their targets while doing business as usual. However, due to the failure of the negotiations at COP-6 and the subsequent recession of the US from the Kyoto Protocol the EU compromised on that issue so that unlimited emissions trading is in fact possible. The only requirement left is that Annex I parties must provide information that the use of the flexibility mechanisms is supplemental to domestic action (UNFCCC 2003b).

However, the US' recession from the Kyoto Protocol means that the most likely biggest demander of permits has left the system. In addition, new emissions estimates imply even lower emissions from the Central Eastern European countries. Furthermore, the Marrakech Accords allow countries to obtain a certain amount of emission permits through carbon sinks from 'Land Use, Land Use Change and Forestry' (LULUCF). Carbon sinks (e.g. forests) take up carbon from the atmosphere so that it does not need to be abated any more. However, many forests in the industrialized world are managed already, so that this implies a windfall gain. All these facts amplify the concern of an oversupply of emissions permits. (OECD 2003, pp. 3-5).

2.2.4.2 Other Flexibility Mechanisms

Joint Implementation (JI) and the Clean Development Mechanism (CDM) are the project-based mechanisms of the protocol. Both mechanisms give the western industrialized countries of the Annex B countries – i.e. the OECD countries – the possibility to invest in emission reduction projects abroad and acquire so-called emission reduction units in the case of JI or certified emission reductions in the case of the CDM. These can be used to fulfill the OECD countries' obligation or can be traded under the emissions trading regime. (UNFCCC 2003b).

The economic rationale behind this is the same as with emissions trading in the sense that abatement should take place where it is cheapest thus minimizing abatement cost. JI focuses at mitigation projects in countries with economies in transition thus creating flexibility within Annex B. It is intended to enhance the inefficient energy technologies in the Central and Eastern European Countries. The CDM focuses on projects in developing countries who do not have to meet quantified emission limitations in the first commitment period (ENB 1997, p. 15). Both project types are intended to be mutually beneficial. The investing countries can obtain emission reduction units at low cost whereas the recipient, or host country of the project would receive technology and know-how contributing to their development. (Oberthür and Ott 1999, pp. 151, 165).

The possibility of a joint fulfillment of a group of Annex B countries under a bubble is due to the European Union. Bubbling means that a group of countries, notably the EU, might redistribute their commitments internally as long as they jointly fulfill their commitment. This has led to a range of emission targets within the EU as wide as -28% for Luxembourg and +27% for Portugal with respect to 1990-levels (Lefevere 2002, p. 23).

2.2.5 Technology in the Diplomatic Process

The convention and the protocol address the issue of technology *transfer* rather than the issue of the development of climate-friendly technologies themselves. Article 4.5 of the convention only explicitly addresses the role of developed countries in the transfer of "environmentally sound technologies" to developing countries. The protocol's attention is on targets and timetables rather than on policies and measures. Article 10(c) of the protocol mentions cooperation in development and transfer of environmentally sound technologies thereby expanding the language of the convention but still without any binding commitment. (Grubb et al. 1999, pp. 127, 139, 151, 233).

At COP-4, the Buenos Aires Plan of Action (see section 2.2.3) established a consultative process on technology transfer that included regional workshops in Africa, Asia and the Pacific and in Latin America and the Caribbean. As part of the Marrakech Accords an expert group on technology transfer was establish to enhance the implementation of Article 4.5 of the convention which culminated in a workshop on an enabling environment for technology transfer in April 2003. (ENB 2003, p. 1; UNFCCC 2003a).

2.3 Modeling, Technology and the Role of Assumptions

Despite the lack of binding commitments in the legal framework it is undisputed that technical change of unprecedented magnitude is required in order to reach the objective of the convention mentioned in section 2.2.2. As discussed in section 2.2.1, scientific evidence demands for much higher emission reductions than the Kyoto targets. Consequently, the Kyoto Protocol should be regarded only as a first step in a process of sequential (yet unknown) commitments towards stronger reductions in the future.

2.3.1 Acceleration of Technical Change

Emissions of GHGs are mainly caused by burning fossil fuels. Technology is considered as a key to achieve the necessary reductions that are mentioned in section 2.2.1. Whereas the Kyoto Protocol's short-term reduction requirements can be met with today's technologies, the long-term reduction requirements call for fundamental changes in the production of energy services. These, in turn, require a long-term effort in Research and Development (R&D) that need to start today so that the new technologies will be available in the future. (OECD/IEA 2000a, pp. 10, 15-6, 31).

Azar and Dowlatabadi (1999, pp. 523-7) illustrate the point. Using a Kaya decomposition, they demonstrate that total emissions depend on four key variables: Population, GDP per capita, energy use per GDP and emissions per energy use. Using current long-term projections for population and GDP growth they calculate that over the next century a combined annual decrease in energy and carbon intensity (i.e. the last two, technology related factors) of at least 3% p.a. would be required to reach an emission profile that is consistent with the ultimate goal of the UNFCCC. Taking into account the historically observed decrease of 0.3% p.a. in carbon intensity, this would leave another 2.7% decrease p.a. to the energy intensity.

The historically observed rates in the decline of energy intensity, however, are much lower. The fastest decline in energy intensity of 1.4% could be observed in the 1970 and 1980, that is, after the oil price shocks. The trend was slowing down thereafter and even reversed in the industrialized countries in the 1990, that is, energy intensity was *rising* in the last decade. These figures illustrate that, the required decline of 2.7% p.a. in energy intensity or any other combined decrease of 3% p.a. of energy- and carbon intensity would mean an unprecedented acceleration of the rate of technical progress. (Azar and Dowlatabadi 1999, pp. 525).

It can be considered very unlikely that this acceleration in the rate of energy- or carbon-related technical change will occur under business-as-usual conditions. Instead, government support will be necessary to accelerate technological progress (OECD/IEA 2000a, pp. 17-18; 2001c, p. 309).

2.3.2 Assumptions in Modeling and Policy Implications

The necessary acceleration of energy- and carbon-related technical change raises the question of adequate policies and of the role that environment-economic modeling might play in decision support. Modeling exercises should be able to identify the relevant factors that stimulate the transition of energy systems and the economy as a whole towards a low carbon trajectory. That is, they should give hints how policies influence the *rate* and the *direction* of technical change.

So far, environment-economic modeling has mostly used exogenous specifications of technical change. A common method is to use an exogenous trend parameter (Autonomous Energy Efficiency Index, AEEI) that leads to autonomous energy efficiency improvement over time. However, acknowledging (i) the endogenous nature of technical change and (ii) the need for a regime change as suggested above an exogenous representation of technical change is unsatisfying since the change in direction and speed of technical change as a reaction to policy is the very object of analysis.

Löschel (2002, p. 106) notes that especially in long-term analysis typical for climate change policy, differences in the specification of technical change may lead to substantially different results. Edmonds et al. (2000, pp. 20-1) provide examples, in which the assumption of accelerated technological developments lower mitigation cost. Dowlatabadi (1998), too, highlights the role of assumptions and in addition analyzes the effect of endogenous technical change on resource recovery and extraction.

In a controversial article, Wigley et al. (1996) propose that it would be cost efficient to delay abatement until cheap abatement technologies have been developed. Grübler and Messner (1998) demonstrate that this ‘wait and see’ – philosophy reflects the assumption of autonomously decreasing technology cost. By incorporating a learning curve approach with up-front R&D investment in a bottom-up model, they show that early investments in and the early use of new technologies is needed in order to enjoy decreasing cost later through technological learning (Grübler and Messner 1998, pp. 505-8).

Assumptions about technology crucially affect policy implications. In models with an exogenous formulation of technical change, cheap abatement technologies come for free at a later point of time. Therefore, these models suggest that it would be cost efficient to delay abatement until these technologies are available. In contrast, in the endogenous formulation of technical change, efforts via investment in and usage of new technologies have to be undertaken in order to *make* these technologies competitive. Without these efforts the new technologies might not occur at all.

2.4 Technical Change and Emissions Trading

Acknowledging that the rate and direction of technical change react to policies and market conditions raises the question of its possible interactions with the Kyoto mechanisms. As stated in section 2.2, these were introduced in order to reduce compliance cost. However, two problems that are mentioned in section 2.2.4.1, might arise with emissions trading when technology is considered endogenous: Supplementarity in connection with hot air on the one hand and post-Kyoto commitments on the other.

As already mentioned, some parties would have favored a restriction or ceiling on emissions trading in order to enhance domestic action. It is feared that in the presence of hot air on the permit market, there would be no incentive to develop and use new environmentally sound technologies. If cheap emission credits substitute for domestic abatement, they lower demand for environmentally sound technologies so that structural changes towards a low carbon trajectory might be slowed down. This way, unlimited emissions trading might hinder innovations. The necessary post-Kyoto emission reductions, however, cannot be achieved with today's technologies, as mentioned in section 2.3.1. Therefore, it is the very structural change that is needed in order to cope with the future challenge.

If emissions trading induced fewer innovations because abatement is made 'too easy' (i. e. too cheap), this mechanism would hinder the accelerated technical change path that would allow for the more ambitious, long-term emission reductions needed to achieve the ultimate goal of the UNFCCC at reasonable cost. If that was the case, emissions trading would lower abatement costs today at the price of higher costs in the future. Therefore, induced technical change might affect the attractiveness of emissions trading significantly and might have important implications for international climate policy.

In this line of thought a stronger constraint – and higher cost – in the short run would be needed in order to provide a stronger incentive to develop environmentally sound technologies. That way, later generations would then be able to enjoy low-cost carbon abatement that would allow for more ambitious reduction targets in the future and a cleaner environment. However, this line of thought cannot be analyzed in a framework with exogenous technology. Therefore, an endogenous presentation of technology is needed.

2.5 Conclusion

This chapter has shown that the flexibility mechanisms have been discussed quite controversially throughout the history of the climate negotiations. The protagonists of flexibility in general, and emissions trading in particular, advocate the expected reductions in compliance cost. The opponents argue that unlimited flexibility would give access to the excess emissions from Russia and Eastern Europe. This would hinder innovations and technical change in the economy because no real abatement effort would be necessary. However, new technologies – energy technologies in particular – and structural change would be needed, in order to comply with future emissions reductions that are necessary to limit global warming. The underlying assumption is that technical change reacts to market conditions, hence, that technical change is endogenous and could by induced by policy.

From a modeler’s perspective, concerned with policy recommendations, this line of reasoning means that a model of climate change policy should be able to capture both, induced technical change and emissions trading in order to analyze their interrelations and the effect of restrictions. However, most models do not and therefore, this is the program for the remainder of the present work.

Part II
Induced Technical Change: Theoretical Background

3 Technical Change: Some Issues

3.1 Approaches to Technical Change

This chapter introduces some basic concepts, definitions and frameworks concerning technical change analysis. It clarifies some basic issues before turning to the innovation and endogenous growth theories. The most common frameworks to analyze new technologies have been innovation theory on the one hand and endogenous, or ‘new’ growth theory on the other (Weyant and Olavson 1999, p. 68; Jaffe et al. 2000, p. 20). However, Grubb (1998, p. 50) introduces the additional categories of system theory and consumer theory.

The innovation theory stresses the private profit incentive and the appropriability of new knowledge within a framework of imperfect competition as the main driver of innovation. The new growth theory – influenced by the innovation theory – incorporates the Schumpeterian profit incentive into an equilibrium framework and attributes private and public properties to new knowledge. Private-good properties result from the appropriability of new knowledge whereas the associated positive externalities (spillovers) represent public-good properties. These spillovers create dynamic increasing returns and therefore generate long-term growth. (Weyant and Olavson 1999, p. 68; Jaffe et al. 2000, p. 20).

3.2 Definition and Measurement of Technical Change

Technical change can be defined as changing input – output relations in the economic process over time irrespective of changes in factor prices and output levels. More specifically, “a technological advance… enables the economy to obtain greater outputs from the same inputs as time proceeds.” (Stoneman 1983, p. 4). Thus, technical change has the same effect as an increase of factor supply. Therefore, technical change is called to be *factor augmenting*.

Consider a neoclassical production function as shown in equation 3-1. Output (Y) is a function of K, L and E, representing capital, labor and environmental inputs (such as energy or emissions), respectively. Furthermore, output is a function of time (t), meaning that production relations might change over time.

3-1 $$Y = F(K, L, E, t)$$

The production function might also be written in the factor augmenting notation as shown in equation 3-2. The time-dependent coefficients A, B and C describe the respective factor augmentation rates over time. That is, the effect of technical change can be attributed to the individual factors of production. (Jaffe et al. 2002, p. 42; Kumbhakar 2002, p. 245; Stoneman 1983, p. 5).

3-2 $$Y = G(A_t K, B_t L, C_t E)$$

The definition shows that technical change actually changes production relations. That should be distinguished from factor substitution. Figure 3-1 shows the example of a two-factor-space with capital (K) and labor (L). The isoquant (y) represents all factor combinations that yield the same output. The cost minimizing factor combination is given by the tangential point of the isoquant with the line (P_K/P_L) representing the relative factor prices[4].

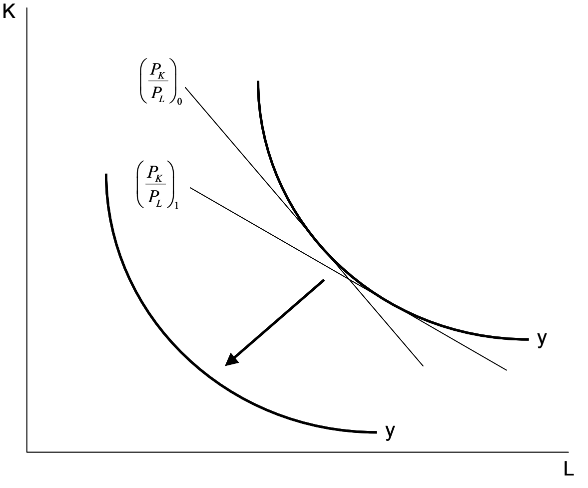

Figure 3-1 Factor Substitution versus Technical Change.
Source: Based on Hillebrand et al. 1998, p. 68.

4 See, for instance, Schumann (1992, p. 157) or any other microeconomic textbook.

Factor substitution as a reaction to changing relative prices, i.e. from $(P_K/P_L)_0$ to $(P_K/P_L)_1$ is a new combination of inputs subject to the current technology, i.e. a movement *along the isoquant* y. Technical change, however, implies a movement *of the isoquant itself* towards the origin. This movement towards the origin is due to the fact that the factor augmenting technical change enables the producer to produce the same output (represented by the unit isoquant) with fewer resources. (Hillebrand et al. 1998, pp. 67-9).

Technical change can either be neutral or *unbiased*, meaning that it does not change the balance between the factors, or it can be *biased* towards certain factors meaning that it augments certain input factors more than others. As will be shown in the chapters 8 and 9, the present work focuses on technical change that is biased towards energy inputs. There are three common definitions of neutrality, called Hicks-, Harrod-, and Solow neutrality. (Barro and Sala-i-Martin 1995, p. 33; Jaffe et al. 2002, p. 42; Stoneman 1983, p. 5).

Technical change is considered to be *Hicks neutral* if the ratio of marginal products remain unchanged for a given *capital/labor* ratio. This can be written as shown in equation 3-3 with A_t indicating the state of technology that grows over time. This kind of technical change is also said to raise 'total factor productivity'.

3-3
$$\begin{aligned} Y &= F(K, L, t) \\ &= A_t \cdot F(K, L) \end{aligned}$$

Another definition focuses on factor shares. Technical change is considered *Harrod neutral* if the relative input shares $K \cdot F_K / L \cdot F_L$ remain constant for a given *capital/output* ratio. F_K and F_L represent the marginal products of capital and labor, respectively. This implies that technical change is purely *labor-augmenting* as shown in equation 3-4.

3-4
$$Y = F(K, L \cdot A_t)$$

Finally, technical change is considered to be *Solow neutral* if the relative input shares $L \cdot F_L / K \cdot F_K$ remain constant for a given *labor/output* ratio. This implies that technical change is purely *capital-augmenting* as shown in equation 3-5.

3-5
$$Y = F(K \cdot A_t, L)$$

Based on these definitions, technical change is labor-saving when labor shares fall whereas capital-saving technical change is associated with falling capital shares. The Cobb-Douglas production function has the special property that it is at the same time Hicks-, Harrod-, and Solow-neutral. Stoneman also mentions different but less common definitions (Barro and Sala-i-Martin 1995, p. 33; Stoneman 1983, pp. 6-7). Binswanger (1978b, pp. 42-3) presents different variants of Hicks neutral technical change.

Furthermore, there are two distinctions of technical change called embodied and disembodied technical change. Technical change is disembodied if the isoquant can shift towards the origin without any changes to the quality of factor inputs. Embodied technical change, however, needs to be introduced by investments in capital or skills. The above concepts of bias are based on disembodied technical change. Since embodied technical change is tied down to factor inputs, the measurement of bias would have to take into account the capital vintages rather than just time. (Stoneman 1983, pp. 4,7).

An early attempt to explain output growth is the growth accounting approach that aims at breaking down the growth rate of aggregate output into contributions of growth rates of the inputs. Barro and Sala-i-Martin attribute one of the first attempts to Solow (1957). An expression that relates output growth to the growth rates of total factor productivity and of the inputs can be derived from equation 3-3. Since the growth in total factor productivity – that is technical change – cannot be measured, it is calculated as a residual, called the ‘Solow residual’. Early growth accounting exercises showed that more than half of output growth was left to the residual implying that technical change plays an important role. (Barro and Sala-i-Martin 1995, pp. 346-7; Grossman and Helpman 1991, p. 6).

So far the definitions of technical change and biases have not said anything about the *sources* of the productivity improvements. This will be subject to the innovation theories in the next chapter.

3.3 Process of Technical Change

More or less all economic theories of innovation and endogenous growth are influenced by the work of Josef Schumpeter (1942). Originally concerned with the explanation of business cycles, he later focused on technical change as a systematic action by the innovative firm to achieve a competitive advantage (Grubb 1998, pp. 54-5).

Schumpeter introduced invention as a purposeful and profit-motivated activity by firms spending resources on Research and Development (R&D). This became to be known as the 'Schumpeterian profit incentive'. Another expression related to his work is the notion of 'creative destruction'. In Schumpeter's analysis, the innovating firm creates a temporary monopoly due to its innovative product. However, when another firm creates an even better product it 'destroys', i.e. replaces the former one. (Nelson and Winter 1982, p. 277; Schumpeter 1934).

Schumpeter (1942) distinguishes three phases of technical change that has been adopted by almost all subsequent innovation theorists: Invention, innovation and diffusion. Invention is the first idea, sketch, or model of a new product or process or, more generally "new ways of doing old or new activities." (Azar and Dowlatabadi 1999, p. 516). Ruttan (2001, p. 65) refers to Usher (1955) by defining inventions "as an act of insight going beyond normal exercise". Inventions may be patented but do not have to. An innovation is the conversion of the invention into a commercial product so that it is available to the market. Stoneman (1983, p. 8) notes that "An innovation…is accomplished only with the first commercial transaction on the market". Inventors and innovators do not have to be identical since an innovator might pick up an existing idea. Diffusion refers to the process when a successful innovation comes to widespread use. That is, innovations usually start in niche applications before they are employed on a wider scale. Diffusion is known to be a rather lengthy process with low adoption rates in the beginning. These are rising as the innovation diffuses and are falling again, when the innovation is in widespread use already. (Jaffe et al. 2002, pp. 43, 46).

Ruttan (2001, chapter 2), drawing on Usher (1955), provides an extensive discussion about the sources of inventions and calls the Schumpetarian distinction "increasingly artificial" (Ruttan 2001, p. 67). He suggests Usher's cumulative synthesis theory as an alternative because "major inventions emerge from the cumulative synthesis of relatively simple inventions". (Ruttan 2001, p. 67).

3.4 Intertemporal Framework of Technical Change

Many decisions today affect future choices and determine future possibilities. This is especially true for long-term issues such as climate change, economic growth and technical and structural change. Therefore, decision making solely from today's perspective without accounting for possible implications for the future might be flawed. Innovating firms seek to maximize the present value of R&D-investments. Households seek to maximize Utility by weighing today's lower consumption in favor of savings against higher future consumption. The latter is equal to the social planner's welfare maximization problem from a macroeconomic perspective. Therefore a framework is needed to analytically connect today's and tomorrows decision.

Ramsey (1928) derived a framework for an optimal consumption and investment path of an infinitely living household subject to an intertemporal budget constraint[5] that was later refined by Cass (1965) and Koopmans (1965). Equation 3-6 illustrates the households decision problem. Today's utility (U) is the aggregate of per-capita utility (u) that is determined by per-capita consumption (c_t) over time and weighted by the discount factor ($e^{-\rho t}$). (Aghion and Howitt 1998, pp. 39-44; Barro and Sala-i-Martin 1995, ch. 2).

3-6 $$U = \int_0^\infty u\left(c_t\right) \cdot e^{-\rho t} dt$$

The decision either to consume or to invest today determines the development of the capital stock in future periods. This, in turn, determines consumption possibilities in later periods. Therefore, there is a trade-off between lower consumption (and higher investment) today and higher consumption possibilities in the future. The discount factor evaluates this trade-off by converting per-capita consumption of different future periods into its present value. It is assumed that households act rationally under perfect information. That is, they have perfect foresight over the whole time horizon.

Discounting incorporates a positive time preference ($\rho>0$) that implies a preference for consumption today rather than tomorrow. Therefore, the later consumption takes place in the future, the less it is valued today. The higher the time preference, the greater value is placed on today's consumption. Most of the growth theory in chapter 5 and the model used in chapters 7-9 is embedded within this framework.

Discounting is a common concept in economics to evaluate and compare all kinds of intertemporal monetary flows. However, choosing an appropriate discount rate is an unresolved issue. Market interest rates are used for conventional economic problems. Climate policy, on the other hand, involves

5 The theory relies on the maximum principle of optimal control, see Barro and Sala-i-Martin (1995, pp. 498-510) or Chiang (1992, chapter 7).

time horizons that last for several generations. It is argued that discount rates should be lower for these long-term environmental projects. Portney and Weyant (1999) and Weitzman (2001) provide an overview over this issue.

3.5 Conclusions

This chapter introduced the basic definition of technical change as perceived by economists. Some definitions of the bias of technical change, Schumpeter's classical description of the process of technical change and the importance of the dimension of time in technical change analysis were introduced as well.

4 Sources of Technical Change: Innovation Theory

4.1 Introduction

Various categorizations of innovation theories can be found in literature. Ruttan (1997, 2001) distinguishes three principal sources of technical and institutional innovation: induced technical change (section 4.2), evolutionary approaches (section 4.3) and path dependency (section 4.4). I will roughly follow Ruttan's categorization by discussing these sources with the main emphasis on induced technical change due to factor endowments. However, I will also consider learning by doing (section 4.5) as a source of technical change (Figure 4-1), although it will be mentioned only briefly.

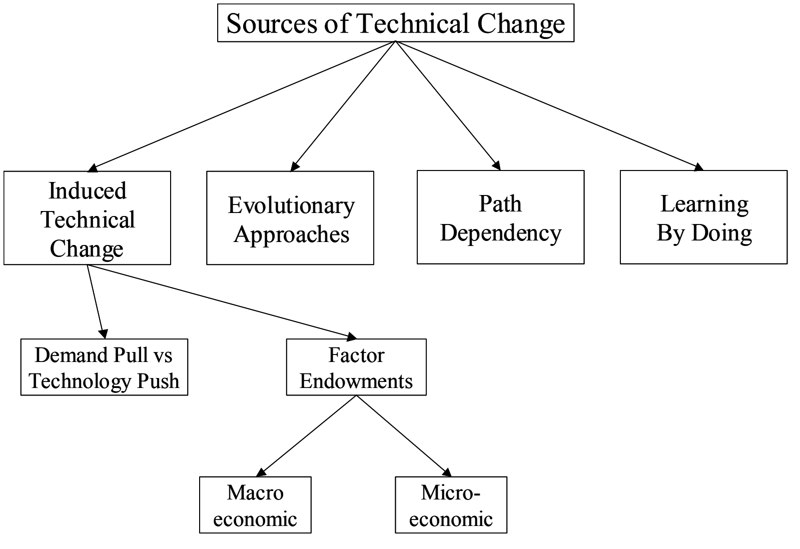

Figure 4-1 Sources of technical change.
Source: Own source, based on Ruttan (1997, 2001).

In the 1960's and 1970's the concept of induced technical change emerged in the theoretical literature. In the 1970's and 1980's, evolutionary approaches where a much discussed source of technical change followed by the notion of path dependency in the 1980's. Within the literature of induced technical change Ruttan (1997, 2001) identifies the main strands of demand pull versus technology push and factor endowments as sources of technical change. The factor endowment perspective, in turn, is divided into a macroeconomic as well as a microeconomic perspective.

4.2 Induced Technical Change

4.2.1 Demand Pull versus Technology Push

The demand pull philosophy states that technical change is triggered by demand for commodities. According to Ruttan (1997, 2001) this can be attributed to works of Griliches (1957) and Schmookler (1962, 1966). It was reinforced by the observation that many technological advances after the Second World War were triggered by the demand for new weapon systems in the United States. The supply push view, on the other hand, states that it is autonomous advances in science and technology that brings about technical change. It was expressed in the believe that basic science provides the knowledge from which applied science develops new technologies. (Thirtle and Ruttan 1987, p. 6, 8).

These two views have been competing throughout time but Thirtle and Ruttan (1987, pp. 9-10) see no need for a discussion of the relative priority of one over the other. Walsh (1984, p. 233) states that the influence of supply and demand factors are both significant but vary over time.

4.2.2 Factor Endowments

Factor endowments as a source of technical change constitutes the neoclassical branch of the induced technical change, or the induced innovation hypothesis. It analyses, under what circumstances technical change might be biased towards a certain factor. The original suggestion is due to Hicks (1932, pp. 124-5)[6] who states that the economic agents aim at economizing the factor that has become relatively expensive. A revived interest led to the formalization of this idea at the beginning of the 1960. Initial approaches

6 According to Jaffe et al. (2000, p. 21, footnote 25) Hicks used the expression of invention in a more encompassing sense and did not make the distinction between invention and innovation as Schumpeter (see section 3.3) did.

centered around a macroeconomic, or growth perspective and were complemented with a microeconomic point of view.

4.2.2.1 Macroeconomic Perspective

The macroeconomic approach was put forward and formalized by Kennedy (1964, 1967), Samuelson (1965, 1966), v. Weizsäcker (1966), Drandakis and Phelps (1966) and summarized in Stoneman (1983, pp. 52-55). It aims at explaining the historic fact that factor shares in the production process remained constant over time despite of rising wages. According to the theory of substitution (cp. Figure 3-1), cheaper capital in relation to labor (i.e. rising wage rates in relation to the price of capital) would lead to a substitution of labor by capital. However, Kennedy (1964, pp. 541-2) notes that the observed fact of historically constant labor shares would require the elasticity of substitution to equal unity which is a priori not necessarily the case.

Kennedy (1966, pp. 543-5) introduces an innovation possibility frontier that establishes a trade-off between the possible growth rates of economy-wide factor augmenting technical change between capital and labor (cp. equation 3-2 for the notation of factor augmenting technology). The optimal rates are derived from the maximization of the unit cost reductions C of the representative entrepreneur, as shown in equations 4-1 and 4-4.[7] They depend on the respective factor shares Π and 1-Π for capital and labor, and on the attached growth rates of factor augmentation over time, denoted a and b and defined in equation 4-2. The dot over the variable denotes differentiation with respect to time.

4-1 $$C = \Pi a + (1 - \Pi) b$$

4-2 $$a = \frac{\dot{A}_t}{A_t}; b = \frac{\dot{B}_t}{B_t}$$

The trade-off between the growth rates is defined in equation 4-3 and shown in Figure 4-2. Maximization of equation 4-1 with respect to a yields equation 4-4. It shows that the optimal slope of the invention possibility frontier decreases with rising labor shares. That is, higher labor shares are associated with higher rates of labor augmenting technical change in relation to capital.

7 Notation from Stoneman (1983, pp. 52-5).

4-3
$$b = \Psi(a)$$
$$\Psi'(a) < 0; \Psi'' < 0$$

4-4
$$\Psi'(a) = \frac{-\Pi}{1-\Pi}$$

Drandakis and Phelps (1966, pp. 831, 837) show that the stability of the equilibrium requires an elasticity of substitution smaller than unity and Stoneman (1983, p. 54) notes that factor prices and factor shares move in the same direction in that case. This was later formalized by Funk (2002) who derives an explicit connection between the microeconomic decision of the innovating firm and aggregated factor shares as shown in section 4.2.2.3 below.

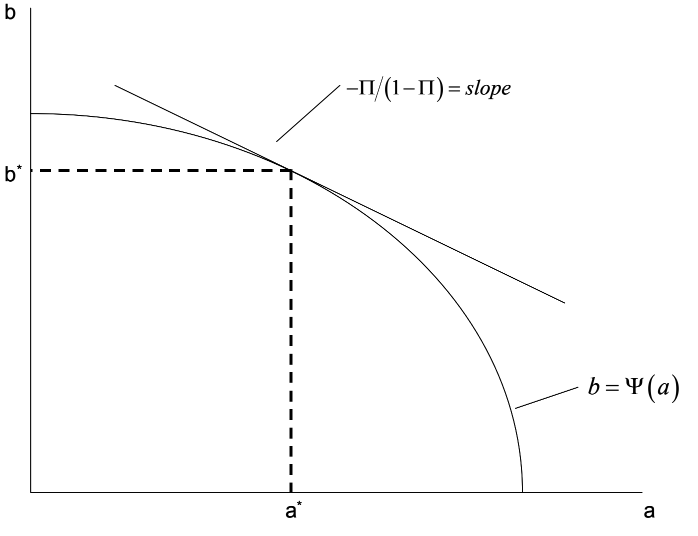

Figure 4-2 Kennedy-model of factor augmenting technical change. Source: Stoneman 1983, p. 53.

Samuelson (1965, p. 348) elaborates the model further and shows that technical change must be purely labor augmenting to ensure a constant profit rate and a constant capital-output ratio. This is because in reality the capital-to-labor ratio increases. In order to maintain constant shares, technical change must be labor-augmenting. Hence the resulting model exhibits the same properties as the classical growth model with exogenous technical change. He also embeds the model into an intertemporal optimization framework as described in section 3.4 above (Samuelson 1965, p. 351).

The grow-theoretic model on induced innovation has triggered much criticism that centered around its lacking microeconomic foundation (Nordhaus 1973, David 1975, Binswanger 1978b, Ruttan 2001). Especially the (non-) derivation of the innovation possibility frontier and the assumptions of its constancy over time that is necessary to derive plausible results where subject to criticism.

Nordhaus (1973, p. 218) calls the microeconomic foundation ‘dubious’. He criticizes that innovation is not modeled as a distinct economic activity requiring resources. He argues that the shift of the production function that represents technical change (cp. Figure 3-1) should not come for free in a theory of endogenous innovation. (Nordhaus, 1973, pp. 210-1).

4.2.2.2 Microeconomic Perspective

The limitations of the macroeconomic model to induced innovation led to the development of microeconomic approaches by Ahmad (1966, 1967a, 1967b), Binswanger (1974, 1978b), Kamien and Schwartz (1968), and Hayami and Ruttan (1985). The microeconomic approach relies more directly on Hicks’ notion of relative factor *prices* as the cause for biased technical change, unlike the macroeconomic approach that focuses on factor *shares*.

Ahmad develops the so-called Hicks-Ahmad model of technical change that is displayed in Figure 4-3. His concept of an innovation possibility curve distinguishes between *possible* production processes under the current state of technology and the one that is *actually chosen* as the cost minimizing process, given relative factor prices.

Figure 4-3 displays the familiar microeconomic graph similar to Figure 3-1. The cost minimizing allocation of the production factors capital and labor is the tangential point of the budget line and the corresponding isoquants. New, however, is the innovation possibility curve (IPC) that illustrates the advancement of technology over time. As knowledge increases from period t to period t+1 the IPC shifts towards the center representing a new set of available processes (or production functions) that could be developed. These new processes are characterized by improved resource productivities as compared to the ones available in t.

From the range of possible processes in period t (i.e. IPC_t) and under the given relative factor prices P_tP_t, the entrepreneur develops the cost-minimizing process I_tI_t that is tangential to P_tP_t. As technology advances over time, a new set of possible inventions is available in t+1 (IPC_{t+1}). Again, the entrepreneur develops the process that is cost minimizing under the given relative factor prices in t+1.

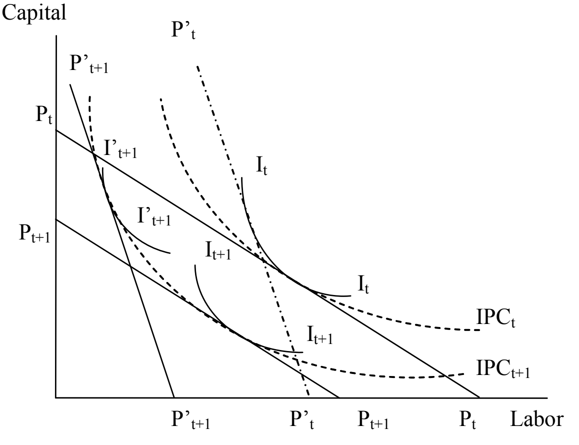

Figure 4-3 Hicks-Ahmad model of induced innovation (amended). Source: Ahmad 1966, p. 349; Binswanger 1978b, p. 27.

If the relative factor prices remain constant as shown by $P_{t+1}P_{t+1}$, the entrepreneur develops the process $I_{t+1}I_{t+1}$ that is, again, cost minimizing and tangential to $P_{t+1}P_{t+1}$. In this situation, the share of expenses on capital and labor remain constant. If, however, the price of labor rises in relation to capital as represented by $P'_{t+1}P'_{t+1}$, the entrepreneur will develop the process $I'_{t+1}I'_{t+1}$ instead. The whole new process or technology $I'_{t+1}I'_{t+1}$ utilizes less labor relatively to capital, hence, technical change is biased towards labor. This is ensured by the convexity of the IPC. (Ahmad 1966, pp. 348-9).

Ahmad assumes that the cost of moving from one process to another along the innovation possibility curve in one period is the same as moving to the new innovation possibility curve in the next period. Since the new set of processes all require fewer resources, the rational entrepreneur will always choose a process on the new innovation possibility curve hence making the current one obsolete once a process is chosen. (Ahmad 1966, p. 348). Therefore, in the event of changing factor prices within t, for instance from P_tP_t to $P'_tP'_t$, it is only rational to substitute factors under the current process I_tI_t so that the tangential point of I_tI_t and $P'_tP'_t$ is reached.

Ahmad further assumes that the new innovation possibility frontier itself is *not* biased towards a specific factor in order to be able to distinguish between the bias of the innovation possibilities and the bias of a particular innovation. If the new innovation possibility frontier itself was biased towards labor, the entrepreneur could develop a process with a bias towards labor saving technical change even in the presence of unchanged relative prices. (Ahmad 1966, pp. 348).

The ability to choose the technology endogenously in the Hicks-Ahmad model is expressed via the elasticity of substitution, i.e. the curvature, of the innovation possibility frontier. A constrained choice of technology due to resource constraints or limited knowledge would be represented by an innovation possibility frontier with almost the same curvature than the isoquants. In this situation, a change in relative factor prices over time could not lead to a significant shift of the isoquants in t+1. (Binswanger 1978a, p. 27). In a multiperiod version of the model the shift of the innovation possibility frontier would occur in a series of steps that could be perceived as a form of learning by doing or learning by using (cp. section 4.5 below). (Ruttan 1996, p. 45).

The model of Kamien and Schwartz (1968) considers a firm with a fixed research budget that maximizes the flow of profits over time. They assume a research production function that alters the parameters of the production function. The parameters represent the total factor productivity, the relative factor weights or the output elasticity, respectively. For a Cobb-Douglas and a CES production function in capital and labor they derive analytically the optimal allocation of the research budget over time. They find that the firms decision to choose neutral or biased technical change depends on the initial technology, relative factor prices and relative research cost.

Binswanger (1974, 1978b) develops a more thorough microeconomic foundation by explicitly defining research processes with research cost and expected pay-off functions. Therefore, the amount and bias of R&D becomes subject to economic optimization. In this more encompassing formulation the entrepreneur can choose the optimal research activity from a portfolio of possible research activities. The models of Kennedy (1964) or Ahmad (1966) can be viewed as special cases of his model (Binswanger 1974, p. 947).

Binswanger argues that the concept of an innovation possibility frontier in the sense of Kennedy (1964) does not hold in the event of costly research. Firms will only invest in research as long as the marginal costs of research are lower than the expected benefits. Therefore, the rational amount of research is reached when marginal cost of research equal expected marginal returns of research. (Binswanger 1974, p. 945).

Figure 4-4 illustrates the point. Starting from the current isoquant II', the entrepreneur could pursue either labor-saving research m or capital-saving research n, leading to the isoquants RR' or QQ', respectively. In the event of a fixed research budget, the two corner points or any combination of the two would lead to a innovation possibility curve that is similar to Ahmad (1966). (Binswanger 1978b, p. 101-2). When the research budget is not fixed, this envelope represents the 'marginal' technologies where marginal cost equal marginal expected benefits.

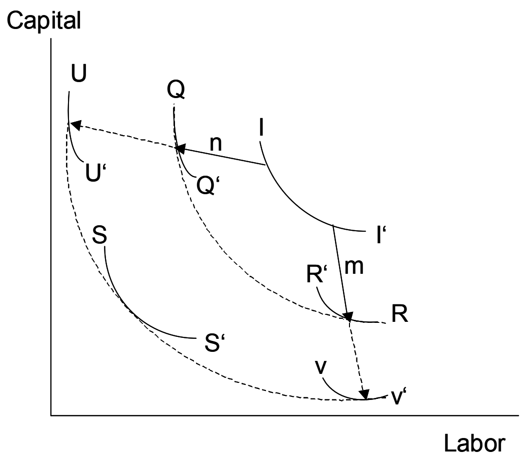

Figure 4-4 Binswanger's model of induced innovation. Source: Binswanger 1978b, p. 102 (amended).

The isoquants UU' and VV' represent technologies with marginal returns of research of zero with respect to capital and labor requirements, respectively.

The isoquant SS' has marginal returns of research of zero for both factors. This envelope is called the scientific frontier. The scientific frontier is empirically unobservable since the rational entrepreneur will not pursue research up to that point as explained above. If marginal returns do not fall to zero the frontier does not even exist conceptually. (Binswanger 1974, p. 945; 1978b, p. 102).

In the one-period version of the model without a research budget constraint, the rates and biases of technical change depend on research cost and total factor cost. In the intertemporal version of the model they depend on the *discounted expected* research and total factor cost. A given output can be produced either by employing the current process or technology as represented by the isoquant II' in Figure 4-4, or by investing in research to develop a new technology. The research budget is not fixed so that any technology within the scientific frontier could be developed. The benefits of research incur in the form of discounted expected cost reductions as long as the process is employed (i.e. the life time of a production plant) whereas the cost of research incur immediately. (Binswanger 1974, p. 947; 1978b, pp. 102-6).

Once a process is installed the capital-labor ratio is fixed and a movement along the isoquant (i.e. factor substitution) incurs additional cost (putty-clay model). The purchase price of capital (R) is fix. Labor cost $(\tilde{W})$ are expressed as the sum of *discounted expected* wage payments. According to the theory of duality between costs and production functions[8] there is a corresponding minimum cost function to each isoquant that relates the minimum cost of production (C^*) to the factor cost and the level of output (Y), as shown in equations 4-5 and 4-6.

4-5 $$C_0^* = YG_0\left(R,\tilde{W}\right)$$

4-6 $$C_1^* = YG_1\left(R,\tilde{W}\right)$$

The subscripts zero and one refer to the initial production function before research with the old technology and the one after research with the improved technology (both without research cost), respectively. Equation 4-7 shows

8 Assumed to be homogenous of degree one. For the duality theory see, for instance, Schumann (1992, p. 168) or any other microeconomic textbook.

that the benefits of research B (without research cost) can be expressed as the difference in the cost of production between the old and the new process.

The innovation possibility function $\psi(\cdot)$ depends on R, $\tilde{W}$ and the amount of labor and capital saving research m and n, respectively. Attaching (constant) factor prices, P^m and P^n, to the two kinds of research and subtracting the research cost results in a maximization problem shown in equation 4-8 in which V denotes the benefits net of cost of research.

4-7 $$B = C_0^* - C_1^* = Y\psi\left(R, \tilde{W}, m, n \right)$$

4-8 $$V = Y\psi\left(R, \tilde{W}, m, n \right) - mP^m - nP^n$$

In this model cost shares – and hence the profitability of cost reducing research projects – are determined by the sum of input requirements weighted by the respective factor prices. Therefore, the expected benefit from R&D efforts and hence, the bias of technical change is determined by both factor prices *and* factor shares. (Binswanger 1978b, p. 99).

A higher expected present value of total factor cost of one factor leads to a bias of research to that factor. It does not matter whether the rise in cost is incurred by a change in the factor price or in the discount rate. This also means that, in line with the Kennedy approach, a high factor share (i.e. a high factor intensity) itself means high factor cost and increases the attractiveness of research biased towards that factor. (Binswanger 1978b, pp. 104-6).

Induced innovation reinforces the price-driven adjustments to output levels and input mixes by re-directing innovative efforts to release scarcity. Therefore, price distortions cause an additional dynamic welfare loss. However, instead of a laissez-faire policy, the government should provide the right institutional framework like publicly funded research and the protection of inventions by patent law. (Binswanger 1978b, pp. 124-6).

Hayami and Ruttan (1970, 1985) claim the existence of a so-called meta-production function. That is, an empirically observable version of the innovation possibility curve. The meta-production function states that factor substitution also involves an element of innovation. This would explain the empirically observed increases in factor productivity that are unlikely to be reached with mere neoclassical factor substitution alone. The meta-production function relates the time horizon with technology choice and substitution possibilities. (Hayami and Ruttan 1985, p. 176).

In the short run technology is fixed and substitutability is low. In the long run the whole fund of existing technology is available and therefore the production relationships can be described by neoclassical production functions. In the very long run, however, all conceivable technologies in addition to the existing ones might be developed and therefore the production relationships can be described by a meta-production function. (Hayami and Ruttan 1985, pp. 134-5, 176).

Hayami and Ruttan perform an empirical test for the bias in technical change in agriculture in the US and Japan for the period of 1880 - 1980. Starting from contrary resource endowments (abundance of land in the US and of labor in Japan), factor-saving technical change was biased towards the relatively scarce input factor in both countries, respectively. Furthermore, despite different trajectories of technical change both countries have experienced similar rapid increases in agricultural productivity that cannot be explained by pure factor substitution along an existing technology. They claim that the key to success was the continuous development of new technologies, that accommodate long-term trends in resource endowments and factor prices. That is, the two agricultural sectors' abilities to perform dynamic factor substitutions along the meta-production functions that accommodates their respective scarcities. (Hayami and Ruttan 1970; 1985, p. 197-8).

4.2.2.3 Microeconomic Foundation for Growth Model

Funk (2002) develops a growth model with an explicit microeconomic foundation of the induced technical change hypothesis. Induced technical change is incorporated into the growth framework by modeling distinct technologies for the individual firm and the aggregate economy. The production function at the firm level exhibits decreasing returns to scale. At the macroeconomic level an aggregate production function is assumed that also contains the individual technology. The research budget and labor supply are fix.

The basic structure of the macroeconomic model is the same as in the case of Kennedy (1964) and Drandakis and Phelps (1966) in section 4.2.2.1. A two-factor production function with associated technology parameters is employed and an innovation possibility frontier as in Figure 4-2 shows the trade-off between the rates of factor augmentation. The optimality condition in equation 4-9 resembles equation 4-4, saying that a higher labor share corresponds with a higher rate of labor augmenting technical progress where -η' is the slope of the innovation possibility frontier, and r and w represent the wage rate and capital price, respectively. The current combination of progress rates represents the current state of knowledge. (Funk 2002, pp. 159-60).

4-9 $$(-\eta') = \frac{w_t L}{r_t K_t}$$

At the macroeconomic level, a constant-return-to-scale technology of the CES type with an elasticity of substitution of $\sigma = 1/(1-\rho) > 0$ is assumed (equation 4-10). The coefficients A and B represent the level of factor augmenting technology of the respective factors. (Funk 2002, pp. 160-1).

4-10 $$\left[\alpha\left(A_t L\right)^{\rho} + (1-\alpha)\left(B_t K\right)^{\rho}\right]^{\frac{1}{\rho}}$$

In the competitive equilibrium of the macro economy with given progress ratios (i.e. state of knowledge) and factor shares the optimal factor price ratio is determined by the marginal factor productivities as shown in equation 4-11. These, in turn, imply the factor share ratio given in equation 4-12. (Funk 2002, p. 162).

4-11 $$\frac{w_t}{r_t} = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{B_t}{A_t}\right)^{\frac{(1-\sigma)}{\sigma}}\left(\frac{K_t}{L}\right)^{\frac{1}{\sigma}}$$

4-12 $$\frac{w_t L}{r_t K_t} = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{B_t K_t}{A_t L}\right)^{\frac{(1-\sigma)}{\sigma}}$$

In each period[9] there is a single small innovating firm that departs from the current state of technology. In the following period, all other firms copy that technology and it becomes the new state of knowledge. Therefore, the choice of the rate and bias of technical progress of the innovator also determines the new state of knowledge in the next period. When the single innovator adopts the new technology, the aggregates remain unchanged due to the assumption

9 At a later stage the model is converted into continuous time.

that the innovating firm is small. (Funk 2002, p. 163). This implies given factor prices even for the innovator who has a monopoly on the new technology.

The assumption that the innovators monopoly only lasts for one period resembles a formalization of Schumpeter's notion of creative destruction (see section 3.3 above) similar to Aghion and Howitt (1992, see section 5.5 below) in the sense that excess profits from the innovation are not sustainable. But in contrast to Aghion and Howitt (1992), Funk (2002, pp. 157-8) assumes small innovating firms instead of large ones which is more in line with Schumpter's early writings.

Due to the assumption that excess profits erode after one period, the innovator maximizes current profits. With the given state of knowledge, given factor shares and with given prices the innovator maximizes the profit function that is shown in equation 4-13. The coefficients $\Delta\mu$ and $\Delta\eta$ represent the growth rates of factor augmenting technology in discrete time.

4-13 $$\max_{L,K,\mu} f\left[\left(1+\Delta\mu\right)A_t L, \left(1+\Delta\eta\left(\mu\right)\right)B_t K\right] - w_t L - r_t K$$

Maximization and transformation in continuous time yields the innovators optimal slope on the possibility frontier with respect to given factor prices and given state of knowledge (i.e. A and B) as shown in equation 4-14. That is, it yields the innovator's optimal rates of factor augmentation for both factors dependent on these aggregate variables. (Funk 2002, pp. 163-5).

4-14 $$-\eta' = \left(\frac{\alpha}{1-\alpha}\right)^{\sigma}\left(\frac{w_t/A_t}{r_t/B_t}\right)^{1-\sigma}$$

However, as already shown in equation 4-11, relative factor prices depend on the current state of knowledge and the current factor input ratio. Inserting equation 4-11 in equation 4-14 yields the innovators choice in terms of the factor supplies. The resulting equation 4-15, in turn, can be modified by inserting the optimal factor shares from the macroeconomic equilibrium in equation 4-12. The resulting expression (equation 4-16) equals equation 4-12, that is, the optimal macroeconomic rate of progress dependent on factor shares. (Funk 2002, p. 165).

4-15 $$-\eta' = \left(\frac{\alpha}{1-\alpha}\right)\left(\frac{B_t K_t}{A_t L}\right)^{\frac{(1-\sigma)}{\sigma}}$$

4-16 $$-\eta' = \frac{w_t L}{r_t K_t}$$

This is the link between the innovator's decision and aggregate factor augmentation rates, hence, the micro-foundation of the growth theoretic model of induced technical change. It answers the question whether the bias in technical change is determined by factor prices or factor shares. The innovators' decision solely depends on relative prices (apart from the state of knowledge). However, the prices, in turn, do depend on aggregate shares on the macro level of the economy. Therefore, the innovators choice is indirectly based on macroeconomic factor shares. (Funk 2002, pp. 165-6).

4.3 Evolutionary Approach

The focus of the neoclassical approaches in the previous section is on the properties of the equilibrium state whereas the evolutionary model focuses on the economic *process* leading to new technologies. The neoclassical models usually assume that the players are perfectly rational, perfectly informed, have perfect foresight and often act under perfect competition. The protagonists of the evolutionary approaches relax these assumptions or replace them by others that they find more realistic (limited rationality, routine). This section mainly focuses on the approach of Nelson and Winter that is the most prominent one and therefore gives only a short overview. It does not claim to be exhaustive.

The renewed interest in the evolutionary approach is attributed to the work of Richard. R. Nelson and Sidney S. Winter who published a series of articles (Nelson and Winter 1973, 1974, 1975, 1977, Nelson et al. 1976) which later cumulated in a book *An Evolutionary Theory of Economic Change* (Nelson and Winter 1982). The model builds on the behavioral theory of the firm and therefore claims to give a better explanation of the black box, i.e. the internal workings of the induced innovation mechanism of the firm. Grubb calls their approach 'neo-Schumpeterian' (Grubb 1998, pp. 50, 71, Ruttan 1997, p. 1522).

Inspired by Schumpeter's interpretation of the process of technical change (cp. section 3.3), the evolutionary model replaces the notion of profit maximization by the concept of the 'routine' that is defined as the regular and predictable business behavior and characterized as a function of various external and internal variables. They also derive an analogy between the role of the firm's routine and biological genes in the selection process (Nelson and Winter 1982, pp. 9-17).

Routines are the firms capabilities and decision rules that might be altered over time either due to random events or as a result of deliberate problem solving according to their search rules. The market acts as the selection process that tends to sort out the less profitable firms from the more profitable ones. The different profitability might cause the firms search rule to be altered if profitability falls below a certain threshold. (Nelson and Winter 1982, p. 4).

The decisive component of the model is the search process. A firm starts research when profits fall below a certain threshold (Nelson and Winter 1982, p. 149). The firm produces with a capital stock and two variable inputs. Coefficients that are associated with the variable inputs represent the technique that determine the respective input requirements. The firm searches for better techniques that lower the input requirements and hence lower costs. Once a new technique is found, the firm performs a profitability test. It only switches to the new process when it is cheaper. Otherwise it stays with the old technology and keeps searching. This search-and-test scheme implies a probability distribution for the technique in the next period dependent on the technique in the current period. (Nelson and Winter 1982, pp. 176, 179).

The probability distribution implies path dependency. It is more likely that the new technique is close to the current one rather than far away. That is, the search is 'local', meaning that modifications of the existing techniques are incremental. Therefore, changes in factor ratios are most likely to be small in the near term. The inertia due to the locality of the search process means that a major change in relative prices implies a gradual change of the firms' factor ratios. If a firm manages the transition faster than others, it realizes greater cost savings and higher growth during that period than other firms. (Nelson and Winter 1982, pp. 179-83).

Nelson and Winter point out that their approach enables a better prediction than the neoclassical model since it contains the relevant elements of the neoclassical theory but goes beyond that. Referring to the well-known argument that rising natural gas or oil prices would induce conservation measures they state:

> It is not, of course, assumed that all oil companies will make the same adaptations…some will be smarter, luckier, or have more favored initial positions than others…a story about firms responding to changed prices by picking a different point in a given choice set is an inadequate metaphor. (Nelson and Winter 1982, p. 185).

In addition to path dependency, the probability distribution for the technique in the next period implies randomness. The profitability check only ensures that the new technique leads to a cost reduction compared with the old one. Apart from that, it is unclear a priori, which technique will be chosen. The firm does not maximize profits like in the neoclassical model but reacts to threats like low profitability. It pursues a trial-and-error process in order to find a superior solution (i.e. technique) in comparison with the existing one. This is a contrasting feature to the neoclassical model that derives an analytically unique and optimal solution.

4.4 Path Dependence

The proposition that technical change is path dependent was put forward mainly by W. Brian Arthur (Arthur 1983, 1989) but also by Paul A. David (David 1975, 1985) and others (Ruttan 2001, p. 112). Ruttan (2001, p. 106) attributes the establishment of the path-dependent model to David. Binswanger (1978a, p. 31 footnote 29) notes that the interrelation between learning by doing and price induced technical change were David's main concern. David highlights the path dependency implied by technological learning and the key role of economies of scale that led to the mechanization of agriculture (David 1975, pp. 4, 6, 65-6). He also presents case studies of lock-in effects (cp. David 1985).

Arthur analyses the process of selection of technologies that exhibit increasing returns to scale. He shows that insignificant events that give an early advantage to one technology may lead to a persistent lock-in effect of that technology. Due to the increasing returns, the early adoption leads to learning effects that further enhances adoption and increases its advantage. The favored technology is locked in whereas the other technologies are locked out. Therefore, history becomes important and competition between technologies takes an evolutionary character because these insignificant events may tip the system into the actual outcome (Arthur 1989, pp. 116, 127-8).

4.5 Learning By Doing

Learning by doing and learning by using takes place after the technical innovation has been adopted. Learning by doing refers to the notion that things can be done more efficiently as experience rises. First noted in the 1930s in the aircraft and shipbuilding industry it was later formalized by Arrow (1962). The closely related notion of learning by using was mainly advanced by Rosenberg (1982, chapter 2) and refers to the idea that the use of a product may lead to incremental improvements in product design in subsequent vintages. (Ruttan 2001, pp. 89-91).

Being neglected for quite a while, the new growth theory of the 1980s incorporated learning by doing and learning by using as a source of long-run growth (see section 5.3 below). Formally, learning by doing can be expressed as decreasing cost of production or increasing productivity as a function of cumulative output or investment. In climate policy modeling, learning by doing can be expressed as decreasing abatement cost when cumulative abatement rises (see section 6.3 below). (Ruttan 2001, pp. 89-93; Goulder and Mathai 2000).

4.6 Conclusions

Most innovation theories presented here model investment in R&D as a purposive process to enhance the profitability situation of the firm. Hence they follow the notion of the Schumpeterian profit incentive. The only exceptions are the path dependent model and the learning-by-doing-model.

The growth theoretic approaches of Kennedy and others were the first attempts to formalize Hicks' notion of biased technical change. However, the model focuses on factor shares rather than on factor prices. The lacking microeconomic foundation that led to the 'implausibility' of the innovation frontier (Ruttan 2001, p. 117) constitutes the major limitation of this theory. Therefore, it is argued that the macroeconomic model did not manage to endogenize technical change in growth theory and can therefore no longer be viewed as an important contribution. (Nordhaus 1973, p. 210; Ruttan 1997, p. 1521; 2001, p. 117).

The lacking microeconomic foundation of the growth theoretic approaches triggered research on the microeconomic foundations of induced innovation. By focusing on factor prices, Ahmad relies more directly on Hicks' notion of induced innovation. Ahmad shows that factor prices do bias factor-saving research towards the high-priced factor. Binswanger improves the microeconomic foundation by introducing research cost and benefits of the firm so that the bias and rate of technical change are both subject to the firms' optimization and depend on factor prices as well as factor shares.

Hayami and Ruttan extend the model to natural resources and also incorporate complementarity. Furthermore, the meta-production function approach gives a plausible explanation for the different technology paths that economies might take with regard to their respective scarcities.

Funk's approach provides the lacking micro-foundation of the macroeconomic innovation possibility frontier. He shows that the small firm's decision of bias is determined by relative factor prices in the sense of Hicks but that these, in turn, are determined by macroeconomic factor shares. Therefore, he connects the macro- and microeconomic approach.

Drawing on the behavior of the firm, the evolutionary approach focuses on the weak part of the microeconomic approach, that is, the research process itself. The concept of routine instead of optimizing firms gives rise to the win-win theory of Porter and v. d. Linde (1995) who state that environmental regulation in one country may improve the firm's competitiveness in that country if policy-induced changes in relative prices induce a threshold effect (Jaffe et al. 2002, p. 45). The evolutionary approach is connected with the path dependent model and share the criticism of neoclassical assumptions.

Finally, learning by doing and – using might create path dependency as well and might explain lock-in effects. Learning by doing and – using depends on the diffusion of technologies since it depends on the technologies cumulative employment or use. Being "a somewhat embarrassing stepchild in the literature on technical change" (Ruttan 2001, p. 92) the learning-by-doing-approach seems to have been neglected for quite a while in the theoretical literature in innovation. However, it plays an important role in incorporating technical change in the new growth theory (cp. section 5.3) as well as in applied modeling of energy-economic and climate-related models (cp. section 6.3.1).

5 Equilibrium Effects of Technical Change: Endogenous Growth

5.1 Introduction

The preceding chapter dealt with the sources of technical change, mainly from a microeconomic perspective. An important feature of those theories is the assumption of complete appropriability of knowledge. That is, knowledge is treated as an entirely private good, hence, there are no spillovers and no external effects. This chapter deals with the equilibrium effects of technical change in a macroeconomic framework. Influenced by insights of the innovation theory, the endogenous, or new growth theory treats R&D as "an endogenous equilibrium response to Schumpeterian profit incentives". (Jaffe et al. 2000, p. 20).

The new growth theory acknowledges that "the asset produced by the research process… is difficult to exclude others from using." (Jaffe et al. 2002, p. 44). Hence, it recognizes that some knowledge spills over to the rest of the economy, that is, it recognizes the partial public-good character of knowledge. The presence of these spillovers alters the result of the neoclassical growth theory that due to decreasing returns to capital long-run growth is not possible.

Neoclassical and new growth theories are concerned with the analysis of the steady state. This is a dynamic equilibrium, where the variables such as output and consumption grow at the same rates. (Aghion and Howitt 1998, p. 8; Barro and Sala-i-Martin 1995, p. 19).

5.2 Neoclassical Growth

The neoclassical growth theory of the Solow-Swan-type showed that an increasing level of technology is needed in order to sustain (empirically observed) long run growth. The assumption of diminishing returns to capital accumulation of the aggregate production function inevitably leads to a halt of economic growth. Growing technology is required as a counteracting effect in order to sustain long run growth (Aghion and Howitt 1998, p. 11; Barro and Sala-i-Martin 1995, p. 12).

Assuming that a two-factor production function in capital and labor (equation 5-1) exhibits constant returns to scale, it can be transformed into per-capita values which yields the so-called intensive form (equation 5-2) where (y ≡ Y/L), (f ≡ F(K/L, 1) and (k ≡ K/L). (Barro and Sala-i-Martin 1995, p. 17).

5-1 $$Y = F(K, L)$$

5-2 $$y = f(k)$$

The evolution of the capital stock K (again, the dot over the variable denotes differentiation with respect to time) is given by investment less the depreciation that is determined by the depreciation rate δ. Under the assumption that households save a constant fraction (s) of their income, investments can be expressed as s·F[10] and the evolution of the capital stock is

5-3 $$\dot{K} = s \cdot F(K, L) - \delta K \ .$$

Transformation of equation 5-3 into the intensive form involves differentiation of the K/L-ratio with respect to time. This yields the expression shown in equation 5-4, where n denotes the growth rate of L over time.

5-4 $$\dot{k} = s \cdot f(k) - (n + \delta) \cdot k$$

Equation 5-4 is the fundamental differential equation of the Solow-Swan model that guides the evolution of the capital stock. Besides the initial capital intensity, it depends on exogenous factors such as the saving rate, the production technology, the growth rate of the labor force and the depreciation rate. The steady state capital intensity k* is determined by setting the growth rate of capital to zero, yielding equation 5-5. It shows that capital intensity does not change when investments exactly offset capital depreciation and population growth. (Barro and Sala-i-Martin 1995, p. 18; Solow 1956, p. 69).

5-5 $$s \cdot f(k^*) = (n + \delta) \cdot k^*$$

Figure 5-1 shows that the system always converges towards the steady state. On the left hand side of k*, returns to capital are higher than the combined

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10 Savings are always equal to investments due to the so-called IS-identity. See, for instance, Felderer and Homburg (1994, p. 128) or any other macroeconomic textbook.

rates of population growth and depreciation. That is, the slope of s·f(k) – which is proportional to f(k) – is higher than the slope of (n+δ)k, meaning that capital intensity increases. On the right hand side of k*, the opposite is true. Therefore, growth cannot be sustained in the long run. It might only rise temporarily when the system converges towards the steady state. Diminishing returns to capital require technical change, that is, a change in f that causes s·f(k) to shift upwards. (Barro and Sala-i-Martin 1995, p. 17-9; Solow 1956, 68-70).

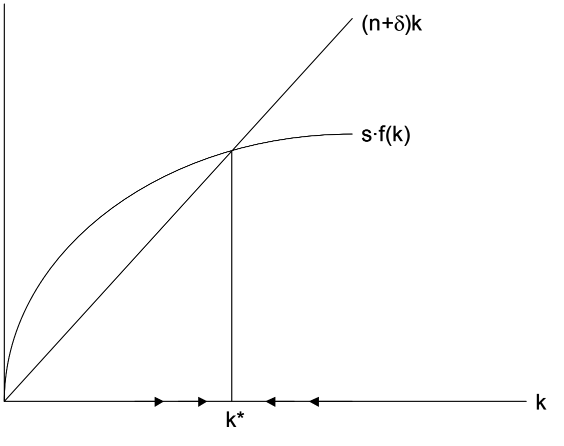

Figure 5-1 The Solow-Swan model.
Source: Barro and Sala-i-Martin 1995, p. 18; Solow 1956, p. 70 (amended).

In order to avoid this kind of result, the class of the so-called AK-models of endogenous growth was developed. The simplest version of these models is described by the production function Y = A·K, where A and K represent the (constant) level of knowledge and capital, respectively. In this simple version, endogenous growth is explained by assumption. Capital is defined in a broader sense including human capital and is characterized by constant returns to capital accumulation. Under this assumption, endogenous growth is indeed possible in the absence of technological change. (Barro and Sala-i-Martin 1995, p. 39).

5.3 Growth Through Learning By Doing

As already mentioned in section 4.5 above, the notion of learning by doing assumes decreasing production cost with rising experience. In his earlier model, Romer (1986) explains higher returns to capital at the macro-level via a certain form of learning by doing in combination with positive spillovers. These spillovers are due to the public good character of knowledge. As shown in equation 5-6, output Y_i of the firm i depends on physical capital K_i and effective labor, that is, on the combination of labor L_i and the labor-augmenting knowledge stock A_i.

5-6 $$Y_i = F\left(K_i, A_i L_i\right)$$

The crucial assumption is that investment in physical capital increases the firm's knowledge stock as a free by-product (learning by investing). The other crucial assumption is that the firm's knowledge stock is a public good. That is, new knowledge that is gained through investment in physical capital in one firm, immediately spills over to the rest of the economy. This spill-over is free for all other firms and thus contributes to the public knowledge stock. Therefore, the *aggregate* knowledge stock K is actually used for the firm's production as shown in equation 5-7.

5-7 $$Y_i = F\left(K_i, K \cdot L_i\right)$$

Physical capital K_i is still subject to diminishing returns. However, the firms' productivity is raised from the spillovers of the other firms' investments that increase the public knowledge stock K. This results in constant returns to capital at the macro level and yields endogenous growth despite of diminishing returns of K_i at the firm level. All firms are assumed to be small. Therefore, K and hence the productivity of labor is given. The approach is embedded into a Ramsey framework of intertemporal utility maximization as explained in section 3.4 above. (Barro and Sala-i-Martin 1995, pp. 146-50; Grossman and Helpman 1991, pp. 35-8; Romer 1986, pp. 1014-23).

Lucas (1988), inspired by Arrow (1962), Uzawa (1965) and Romer (1986) develops a two-sector model of endogenous growth by introducing a separate sector for human capital accumulation. That is, he employs different technologies for human capital accumulation and for final good production. (Aghion and Howitt 1998, p. 27; Barro and Sala-i-Martin 1995, p. 182; Ruttan 2001, pp. 25-6).

Lucas develops two variants of the model. In the learning by doing version, human capital accumulates due to the production of the final good. Lucas assumes two consumption goods, c_1 and c_2, that are produced by a Ricardian technology without physical capital as shown in equation 5-8. This technology employs human capital (h_i), specialized to the production of the respective good, and the fraction u_i of the total workforce (N; assumed to be constant) that is devoted to the production of c_i. (Lucas 1988, pp. 27-8).

5-8 $$c_{i,t} = h_{i,t} \cdot u_{i,t} \cdot N$$

5-9 $$\dot{h}_{i,t} = h_{i,t} \cdot \delta_i \cdot u_{i,t}$$

According to equation 5-9, human capital grows in proportion with the fraction u_i of the workforce that is devoted to a certain product. If only one good is produced, human capital for this production process accumulates with its maximal rate δ_i. (Lucas 1988, pp. 27-8).

In the other version, called the schooling model, workers allocate their time between either production or human capital accumulation (schooling). That is, they employ either more of their current human capital on current production of the final good or they can augment their human capital stock which in turn leads to higher productivity and output in later periods. (Lucas 1988, pp. 17-9).

The advantage of the learning by doing approach is that there is no need to deal with increasing returns to scale. As in the Solow-Swan world, the model relies on a neoclassical production function that exhibits constant returns to scale to the two factors K and L (i.e. the output elasticities of K and L add up to one). An endogenous knowledge stock would require the contribution to that knowledge stock to be subject to utility maximization in the same manner as e.g. to physical capital. Since the two-factor production function exhibits constant returns to scale, the inclusion of an additional factor would mean increasing returns to scale (i.e. the output elasticities of K, L and A would be greater than one). The notion of learning by doing avoids this effect by assuming that the accumulation of the aggregate knowledge stock is an unintended by-product. (Aghion and Howitt 1998, p. 23; Barro and Sala-i-Martin 1995, pp. 149-50).

An important feature of these models is their sub-optimal solution due to the positive spillovers. Since knowledge is a positive externality, private returns to capital accumulation are lower than social returns. The producers of knowledge are not fully rewarded for their efforts as in the case of full competition. Thus, the efforts to accumulate capital and the associated knowledge stock, growth rate and per capita consumption turn out to be too low. A social optimum would require e.g. subsidies on purchases of capital or subsidies on production. (Aghion and Howitt 1998, pp. 28-9; Barro and Sala-i-Martin 1995, pp. 149-50).

5.4 Growth Through Increasing Product Variety

Despite of the advantages mentioned above, the learning by doing specification does have a significant drawback: Learning by doing does not explain technological development as a purposive process. Furthermore, it is a rather strong assumption that the pure accumulation of capital – even in the broader perception that includes human knowledge – never runs into diminishing returns. Therefore, the following approaches treat technical change as the result of a deliberate process, namely the investment of research and development (R&D).

Endogenous growth models of the 'love of variety'-type generate long run growth by technical change in an intermediate good sector. Romer (1987, 1990) applies the variety theory of Dixit and Stiglitz (1977) to avoid diminishing returns. Technical change comes from an expansion of the intermediate sector through the creation of new variants of intermediates. (Barro and Sala-I-Martin 1995, p. 213; Romer 1987, pp. 56-7 and 1990, p. S80, S83). As can be seen in equation 5-10, final output (Y) is produced by a Cobb-Douglas production function with labor (L) and N different types of intermediates[11]. The parameter A describes the general level of technology.

5-10 $$Y_i = A \cdot L_i^{1-\alpha} \cdot \sum_{j=1}^{N} \left(X_{ij} \right)^{\alpha}$$

Technical change is generated by an increase in the number N of the intermediate goods. In equilibrium all variants are employed in the same quantity ($X_{ij}=X_i$), yielding equation 5-11. The intermediate good sector could be expanded either by an increase in X or an increase in N. The former implies

11 The Notation is taken from Barro and Sala-I-Martin (1995, p. 213-4). Romer (1990, p. 80-1) talks about 'producer durables'.

a heavier utilization of one particular intermediate whereas the latter implies the utilization of a greater variety of intermediates.

5-11
$$\begin{aligned} Y_i &= A \cdot L_i^{1-\alpha} \cdot N \cdot X_i^{\alpha} \\ &= A \cdot L_i^{1-\alpha} \cdot \left(NX_i\right)^{\alpha} \cdot N^{1-\alpha} \end{aligned}$$

Equation 5-11 shows that an expansion of the intermediate sector through an increase in X exhibits decreasing returns to scale. However, the term $N^{1-\alpha}$ in equation 5-11 indicates that an increase in N also increases Y_i. Therefore, expanding the *variety* of intermediates avoids diminishing returns. The new intermediate good is neither a direct substitute nor a direct complement for the existing one. That is, it is assumed to be a 'breakthrough' innovation. (Barro and Sala-i-Martin 1995, p. 213-4). This is expressed in the additive separable specification of the intermediate sector in equation 5-10. (Romer 1990, p. S81, S88).

Each intermediate good is produced by a monopolist. Fixed cost that stem from sunk cost of product development introduce increasing returns to scale which implies imperfect competition. The profits to be earned under such circumstances provide an incentive for the firms to engage in research. Innovators maximize the net present value of the infinitely living intermediate. That is, Romer included increasing returns to scale in an equilibrium framework. The creation of knowledge (i.e. research) became a deliberate process due to profit maximizing behavior. (Aghion and Howitt 1998, pp. 36-7; Barro and Sala-i-Martin 1995, p. 216; Romer 1990, S81-2, S86-7).

The high intensity of human capital in R&D is accounted for by assuming that the intermediate good is produced by labor only. Endogenous growth stems from the assumption of declining cost of new ideas (i.e. new intermediate products) as the amount of knowledge (i.e. the sum of intermediate products) increases. This specification yields intertemporal spillovers as today's research lowers future research cost and represents another source of increasing returns to scale. (Barro and Sala-i-Martin 1995, p. 227-8; Romer 1990, p. S83-4).

Like the learning by doing specification in section 5.3 above, this type of model also yields an equilibrium solution that is not optimal. Again, investment in knowledge is too low from a social perspective and yields lower growth rates and per capita consumption than optimal. The imperfections stem from two sources: First, due to its monopolistic structure, the intermediate sector supplies fewer innovations at higher prices than socially optimal and second, due to the intertemporal spillovers, research efforts are not fully rewarded. However, the monopolistic structure and associated rents constitute the very incentive to innovate i.e. under perfect competition there would be no innovation at all (Barro and Sala-i-Martin 1995, p. 229).

For reasons of simplicity, Barro and Sala-i-Martin present a version of the model where the intermediates are non-durables but note that the results are similar to the original version with respect to the determinants of technical change and economic growth. They also assume that intermediates are produced by units of output instead of human capital alone. Furthermore, in their specification, the monopolized intermediates become competitive in later periods according to a certain probability. This partial loss of monopolistic profits due to the erosion process of market power further increases the gap between private and social returns. This results in an even lower incentive to innovate so that the resulting market failure is even greater. (Barro and Sala-i-Martin 1995, pp. 215, 224).

Grossman and Helpman (1991, ch. 3) demonstrate that endogenous growth in the product variety model depends on the assumption of spillovers. They present model versions with and without spillovers. In the model version without spillovers, firms eventually lose the incentive to invest in R&D because the development of new products lowers the profit rate until it eventually reaches the discount rate. They attribute this 'neoclassical result' of diminishing returns to factor accumulation to the neoclassical treatment of knowledge as an entirely private good. In their version with spillovers, knowledge becomes a public input to R&D, which increases over time due to rising product variety. This in turn leads to decreasing cost (in line with Romer) because less labor input is needed. Again, spillovers offset diminishing returns of factor accumulation.

5.5 Growth Through Increasing Product Quality

A different way to generate endogenous growth is not to expand the variety of intermediates as in section 5.4 above but to model improvements in the intermediates' quality. Rising product quality can be perceived as gradual innovations of existing products whereas the generation of new variants (as in the Romer model) could be perceived as basic or radical innovations. Unlike radical innovations, gradual improvements of the same products tend to be close substitutes to the old ones. This feature of close substitutability results in the replacement of the older version of the intermediate once the new one is developed. Thus, the 'creation' of the new product 'destroys' the old one. This process of technical change mirrors Schumpeter's notion of 'creative destruction' (Schumpeter 1934) described in section 3.3 above. It was formalized by Aghion and Howitt (1992, 1998). (Barro and Sala-i-Martin 1995, pp. 240-1).

In the notation of Barro and Sala-i-Martin (1995, pp. 240-62), the setup of the model is in many respects similar to the specification of the model with increasing product variety. The production function displayed in equation 5-12 is almost identical to equation 5-10. Like in section 5.4 above, there is an intermediate sector with a monopolistic structure and again, expected monopoly rents provide an incentive to devote resources to R&D. The only difference in this case is that the number of variants (N) are assumed to be constant and that $\tilde{X}_{ij}$ represents the *quality-adjusted* amount of the jth intermediate good. (Barro and Sala-i-Martin 1995, p. 242).

5-12 $$Y_i = A \cdot L_i^{1-\alpha} \cdot \sum_{j=1}^{N} \left(\tilde{X}_{ij} \right)^{\alpha}$$

The distinction to the model of Romer is that R&D increases the intermediates' *quality*. Equation 5-13 shows that quality improvements are modeled as increases of a quality index q^k, attached to X_{ij} in each sector. Therefore, rising quality increases the productivity of the intermediate good that in turn results in growth of final output. (Barro and Sala-i-Martin 1995, p. 243).

5-13 $$\tilde{X}_{ij} = \sum_{k=0}^{K_j} \left(q^k \cdot X_{ijk} \right)$$

The exponent k represents proportionately spaced quality rungs on a quality ladder as shown in Figure 5-2. A successful incremental innovation is represented by a move to the next rung. The successful 'creation' 'destroys' the old one. That is, the improved intermediate good substitutes the old one and the current innovation is the only intermediate good produced in each sector. The innovator is the only supplier of the new intermediate until another innovation replaces it. This results in a temporary nature of monopoly rents. (Barro and Sala-i-Martin 1995, pp. 241, 244). The improvement of an intermediate good by a competitor leads to a shift of monopoly rents from the current 'state-of-the-art-producer' to the new one.

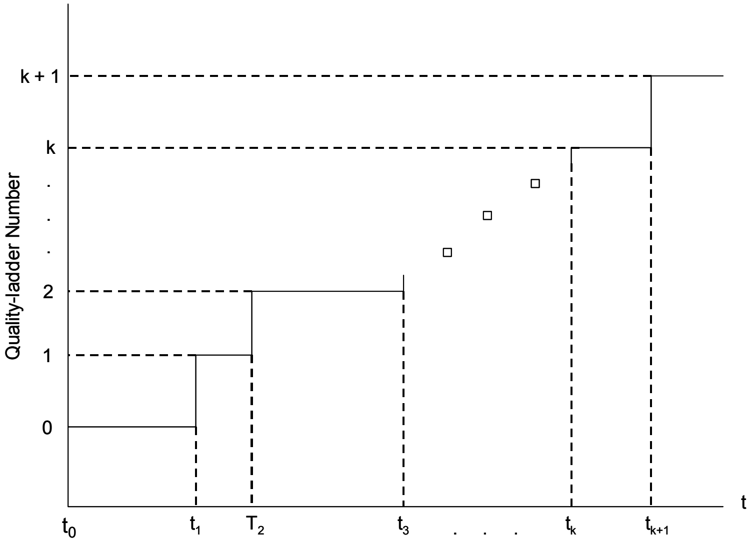

Figure 5-2 A quality ladder in a single sector.
Source: Barro and Sala-i-Martin 1995, p. 243.

Similar to equation 5-11 it can be shown that in this model the improvements in quality, i.e. a rise in k, is the key to growth. From the marginal product of the 'state-of-the-art-intermediate' (the only one in use) in each sector and from the assumption of markup pricing due to the monopolistic structure, it is possible to derive an expression for optimal output of the jth intermediate dependent on k. Substitution of this expression into the production function (that employs only the latest version of the intermediate) and rearrangements of terms yields

5-14
$$\begin{gathered} Y = A^{\frac{1}{(1-\alpha)}} \cdot \alpha^{\frac{2\alpha}{(1-\alpha)}} \cdot LQ \\ Q \equiv \sum_{j=1}^{N} q^{\frac{k_j \alpha}{(1-\alpha)}} \end{gathered} \quad .$$

The index Q is an aggregate quality index. It represents a combination of the various quality improvements (k) that may be different in the different sectors of the economy. The index rises with rises in k. Since L and N are constant, output rises with rises in k.

The current innovator is able to make a profit until another innovator replaces his product. Therefore, the innovator has to weigh the net present value of the flow of profits for the expected time span against the expected cost to innovate. Uncertainties in research are modeled by a poisson process in which the probability of a new innovation depends on the current R&D effort. That is, the higher the R&D effort is, the higher is the probability of success, meaning that the probability is independent of previous successes in research. (Barro and Sala-i-Martin 1995, pp. 244, 246-7).

The temporary nature of the monopoly rents is a key feature of this framework and leads to two opposing incentives on R&D. First, the expected return from R&D (and therefore the incentive to devote resources to it) varies with the duration of the monopoly. This leads to under-investment in R&D because unlike the monopoly rents the technical progress is not temporary to society. Second, part of the return from the monopoly rent does not result from increased productivity but from a redistribution of existing monopoly rents. This, in turn, leads to over-investment in R&D (Barro and Sala-i-Martin 1995, p. 242).

5.6 Conclusions

The endogenous growth theory tries to overcome the diminishing returns to capital that leads to a halt of growth in the neoclassical Solow-Swan-Model. Several approaches have been introduced in the literature on endogenous growth. Learning by doing creates a macroeconomic knowledge stock that exhibits constant returns. Increasing product variety due to radical innovations avoids a too intense utilization of every single intermediate, thereby avoiding diminishing returns. Replacements of old products due to incremental innovations has the same effect.

In the learning-by-doing-model the knowledge stock is an unintended by-product of investment. In the latter two approaches the profit incentive in a framework with imperfect competition provides the incentive to innovate. Furthermore, all these approaches incorporate some form of positive spillovers as a source of growth. In the learning-by-doing-model investments in the firm’s capital stock spill over as knowledge to the rest of the economy. The models with an intermediate good sector exhibit intertemporal spillovers due to improved cost/benefit relations as knowledge increases. These spillovers and learning effects lead to sub-optimal outcomes of the models.

The inclusion of uncertainty in the model of creative destruction is an important aspect since investments in R&D are subject to high uncertainties. Moreover, the distribution is such that investments in R&D yield "very low-probability but very high-value outcomes" (Jaffe et al. 2002, p. 44).

Part III
Applications to Climate Policy

6 Induced Innovation and Climate Policy Modeling

6.1 Introduction

The two previous chapters have shown the treatment of technical change in economic theory. The main outcome of the innovation theories in chapter 4 was that technical change – apart from learning by doing – is a purposeful, profit-motivated activity. Chapter 5, in turn, showed how the insights of the innovation theories where incorporated in theoretical macroeconomic equilibrium models in order to analyze their effects on long-run growth.

Acknowledging that innovative efforts respond to economic constraints has important implications for climate policy. Taking relative prices as a measure of scarcity, the induced innovation hypothesis implies that raising the relative prices of carbon-containing fuels would re-direct innovative activity towards carbon-saving technologies. Therefore, climate policies, such as carbon taxes or tradable emissions permits, would provide measures to enhance the transition of energy systems towards a low carbon trajectory.

From a firm's point of view the introduction of such policies constitutes a "carbon price premium" (Sanstad 2000, p. 9), that is, additional cost of using fossil fuels. This yields an additional incentive to develop carbon saving technologies in addition to factor substitution and autonomous trends. The development of carbon-saving technologies contributes to the firms' search for new profit opportunities and strategic advantages. (Carraro 2000b, p. 272; OECD/IEA 2001, p. 11).

6.2 Model Types

There are several conceivable ways to categorize economic-environmental models. Weyant and Hill (1999, xix-xxii), for instance, categorize them by their treatment of carbon/energy on the one hand and the rest of the economy on the other. The most common classification, however, is the distinction between the bottom-up and the top-down approach. Both classes have their merits and shortcomings and the appropriateness depends on the research question one tries to answer. They will be described shortly but since the main focus of the present work is on modeling technologies, the next section categorizes the models by the way technologies are modeled.

Bottom-up models are engineering-based and they focus on a detailed description of the energy sector. A number of distinctive energy technologies and their economic performances are explicitly modeled. Technical change occurs in these models by the replacement of one technology by another due to better economic performance. However, the rest of the economy is only modeled in a rudimentary manner so that the interdependencies with other economic sectors are only reflected to a limited degree. Therefore, bottom-up models are better suited for short and medium term projections and for detailed predictions of the energy sector rather than for the projections of long-term changes of the economy as a whole. (Edmonds et al. 2000, p. 13; Löschel 2002, p. 108; Messner 1997, p. 292).

Top-down models, on the other hand, focus on the representation of the economy as a whole. The sectors are characterized by aggregated production or cost functions rather than by detailed descriptions of single technologies. Therefore, this model class is less suitable for the analysis of single technologies. Top-down models are more suitable for long-term projections. Technical change is represented by price driven productivity improvements of input factors (Edmonds et al. 2000, p. 13; Löschel 2002, p. 108; Messner 1997, p. 292). The strength of top-down models is their focus on the interrelations between the sectors that reveal the incentives for technical change. These interrelations allow for predictions in the longer term since they capture the economic effects of technical change on the whole economy.

6.3 Approaches of Modeling Induced Innovation

There have been attempts to model technical change in an endogenous fashion in bottom-up as well as in top-down models related to climate change. Two main strands of modeling induced technical change can be observed in the literature of applied modeling: learning curves and investment in R&D.

Learning curves rely on the assumption of learning by doing as explained in sections 4.5 and 5.3. In the environmental-economic literature, technological learning often applies to the cumulated production of specific energy production technologies. That is, learning curves have been attached to certain technologies. These reflect decreasing cost of energy production in relation to cumulative investment in, or installed capacity of that technology. Another variant is that abatement cost of greenhouse gases decrease due to cumulative abatement.

Investments in R&D build on the recognition that energy-related knowledge or technology diminishes the trade-off between factor scarcity and economic growth. Hence, it contributes to the goal of profit or utility maximization. In the literature, these investments in R&D are usually modeled as additional capital stocks of human or knowledge or research capital. The new capital stocks augment either total factor productivity or the productivity of certain input factors (energy or carbon among them) or both.

In a much cited article, Goulder and Mathai (2000) present two versions of an analytical model of knowledge accumulation through R&D and learning by doing, respectively, where an increasing level of a knowledge stock H lowers marginal abatement cost. Apart from the rate of autonomous progress α and the historical knowledge stock H_t, the development of the knowledge stock over time depends on the knowledge accumulation function Ψ. The parameter k determines whether there is induced technical change, which is the case if k > 0.

The R&D-version of knowledge accumulation is shown in equation 6-1 where the knowledge accumulation function Ψ depends on current investments in knowledge I_t (Goulder and Mathai 2000, p. 5).

6-1 $$\frac{\partial H}{\partial t} = \alpha_t H_t + k\Psi\left(I_t, H_t\right)$$

The case with learning by doing is specified in equation 6-2. All else equal, the knowledge accumulation function Ψ depends on cumulative abatement A_t instead of current investment I_t (Goulder and Mathai 2000, p. 11). Therefore, in the first case additional resources have to be devoted to R&D via investments whereas in the second case new knowledge is created as a free by-product of (cumulated) abatement itself.

6-2 $$\frac{\partial H}{\partial t} = \alpha_t H_t + k\Psi\left(A_t, H_t\right)$$

Using a carbon tax both versions are used to estimate total costs and optimal abatement paths to reach an *exogenous* CO_2 concentration target (cost-effectiveness-criterion) and to estimate an *optimal* CO_2 concentration target (cost-benefit-criterion) as compared to the case without induced technical change (i.e. k = 0). They also perform numerical simulations which reinforce their analytical findings.

In all scenarios, induced technical change lowers overall costs as well as optimal taxes. Optimal overall abatement rises under the cost-benefit-criterion. (Goulder and Mathai 2000, pp. 15, 30). In the R&D-version, the presence of induced technical change leads to a partial postponement of abatement for both criteria, that is, initial abatement is lower than without induced technical change but is higher later on (Goulder and Mathai 2000, pp. 10, 17). In the version with learning by doing, postponement is uncertain so that initial abatement might even be higher with induced technical change if the influence of learning by doing is strong enough (Goulder and Mathai 2000, pp. 13, 18).

I now turn to an overview of modeling technical change according to these two approaches. Learning curves are often modeled in bottom-up models whereas investments in R&D can often be found in top-down models. However, there are exceptions to this rule.

6.3.1 Learning Curves

Learning curves are often applied to bottom-up models because they can be attached to individual technologies. In the MESSAGE model, Messner (1997), and Grübler and Messner (1998) employ an endogenous non-linear learning curve that reflects decreasing costs of employing specific energy technologies as commercial investments and installed capacities accumulate. Similar approaches were taken in the MARKAL model (Barreto and Kypreos 1999) and the ERIS model (Kypreos et al. 2000) where specific investment costs of energy production were modeled as a decreasing function of cumulative installed capacity. Within an effort to develop a common methodology and to harmonize assumptions and data for a wide range of energy systems models (Capros and Vouyoukas 2000), the same type of learning curve as shown in equation 6-3 was implemented in a common effort in the models ERIS, MESSAGE and MARKAL. (Kram et al. 2000, p. 51).

6-3 $$SC\left(C\right) = a \cdot \left(\frac{C}{C_0}\right)^{-b}$$

Specific investment cost of energy production (SC) is modeled as a decreasing function of cumulative installed capacity C. In this specification, the parameter a represents specific investment cost. The parameter -b represents the elasticity of specific investment cost with respect to the cumulative capacity, that is, the learning index for the technology. The learning index indicates the amount of cost reduction per doubling of capacity. Kram et al. (2000, p. 63) conclude that the models tend to favor the early development of those technologies that are better suited to cope with the changing relative cost occurring due to environmental policy.

Kypreos (2000) and Bahn and Kypreos (2002) use a similar specification for the MERGE model. Manne and Richels (2002) conclude that the inclusion of learning by doing does have no effect on timing but lowers cost of optimal carbon abatement policies. Lako et al. (2002) extend the learning curve in MARKAL to clusters of technology, that is, a group of similar technologies.

Gerlagh and v. d. Zwaan (2002, 2003) and v. d. Zwaan et al. (2002) combine a top-down model with a learning-curve approach. The model DEMETER (DE-carbonization Model with Endogenous Technologies for Emission Reductions) is an aggregated top-down macroeconomic model, which includes two different types of energy technologies (E_i,), namely a fossil energy technology E_F and a non-fossil energy technology E_N (v. d. Zwaan et al. 2002, p. 3). Exhibiting properties such as endogenous energy demand on the one hand and two distinct energy technologies with attached learning curves on the other, the model combines features of top-down and bottom-up models (Gerlagh and v. d. Zwaan 2003, p. 54).

The learning curve influences the amount of required capital and the maintenance efforts for energy production. The production of energy for both technologies is related to energy specific capital stocks K_i as well as maintenance and operation efforts M_i. The capital stocks need to be built up by investments and are subject to depreciation. Equations 6-4 and 6-5 show that without the learning curve function g(x) changes (in absolute terms) in energy production (denoted by ~) would require proportional changes in energy capital stocks as well as maintenance and operation efforts, whereas a_i and b_i represent capital and maintenance intensity, respectively (v. d. Zwaan et al. 2002, p. 8).

6-4 $$\tilde{K}_{i,t} = g\left(x_{i,t}\right) a_i \tilde{E}_{i,t}$$

6-5 $$\tilde{M}_{i,t} = g\left(x_{i,t}\right) b_i \tilde{E}_{i,t}$$

6-6 $$g\left(x_i\right) = g_0 x_i^{\alpha-1} + 1$$

With the learning curve g(x), less capital and maintenance is required as cumulative capacity increases. As shown in equation 6-6 and due to $\alpha < 1$, function values decrease with rising cumulative capacity x_i of energy production of the respective energies (i) and converge to a floor price of 1. Therefore, capital and maintenance requirements depend on experience with the respective technologies. Due to the learning curve private investment costs are higher than social costs. That is, optimality would require subsidies on investment. (v. d. Zwaan et al. 2002, p. 9).

Both technologies have the same learning potential with 20% cost reduction per doubling of usage. However, due to their greater usage, the fossil fuels start out at lower cost levels but also enjoy lower decreases in cost. The non-fossil fuels, on the other hand, start out at higher cost but enjoy stronger decreases in cost due to their fewer usage. (Gerlagh and v. d. Zwaan 2003, p. 45).

Due to the endogenous technological change, there are earlier emission reductions than with static technologies (that is, equations 6-4 and 6-5 without g(x)). Moreover, the effect is stronger than in bottom-up models (v. d. Zwaan et al. 2002, p. 17). Learning by doing leads to lower production cost which implies lower optimal tax levels on the carbon technology. However, the learning curve means that the early use of the carbon free technology is required in order to provide the basis for cost reductions in the future. Therefore, an optimal policy is recommended that focuses on investment subsidies for the carbon free technology in the short term rather than carbon taxes. (v. d. Zwaan et al. 2002, pp. 17-8).

Gerlagh and v. d. Zwaan (2003, pp. 55-6) point out that their results depend on four assumptions that reflect the combined features of top-down and bottom-up approaches:

- Reducing energy demand constitutes an option to reduce abatement cost that is not available in bottom-up models with usually fixed energy demand.
- Learning by doing creates intertemporal spillovers (see also section 5.3 and 5.6).
- The assumption of the two energy technologies (fossil and non-fossil) being good but imperfect substitutes ensures positive demand for both technologies despite of differences in prices. This assumption ensures the

existence of a niche market for the (more expensive) non-fossil technology so that it can benefit from early learning effects.
- Carbon taxes resulting from climate policy partially internalize the intertemporal spillovers that result from increasing knowledge over time, meaning that they partially correct this market failure (see also section 5.3 and 5.6).

Gerlagh and v. d. Zwaan (2002) perform a sensitivity analysis and find that the result of earlier abatement is robust under most parameter values. However, the robustness is mostly affected by uncertainties in the learning rates of the two technologies and in the elasticity of substitution between the two technologies.

Rasmussen (2001) presents another example for a top-down model with a learning curve. He incorporates learning by doing in renewable energy in a multi-sector dynamic general equilibrium model for Denmark. The learning curve affects the economies of scale of a renewable energy capital stock and is calibrated in order to match projected cost reductions for wind-based electricity production (Rasmussen 2001, p. 298). As shown in equation 6-7, output Y_t of renewable energy capital is affected by the level of knowledge related to renewable energy A_t and by min(·) representing the cost minimizing shares of intermediate inputs. (Rasmussen 2001, p. 304).

6-7 $$Y_t = A_t^{\gamma} \min\left(\bullet\right)$$

6-8 $$A_t = A_{t-1} + \eta Y_{t-1}^{\lambda} A_{t-1}^{\phi}$$

The level of knowledge A_t, in turn, is subject to learning as shown in equation 6-8. It depends on the historical knowledge stock A_{t-1}, on the previous output Y_{t-1} of the renewable energy capital stock and on the effect of earlier research A^{ϕ}_{t-1} (Rasmussen 2001, p. 305). The presence or absence of learning by doing in the model is specified by setting $\eta = 1$ or $\eta = 0$, respectively. The parameter λ governs the magnitude of the contribution of output to the knowledge stock.

The effect of earlier research is determined by the parameter ϕ. A positive contribution of previous research to the current knowledge stock, which makes future research easier and which is known as ‘standing-on-shoulders’, is modeled by positive values for ϕ. A ‘fishing out’ specification, which means that previous knowledge accumulation diminishes the opportunities for future discoveries is modeled by negative values for ϕ.

6.3.2 Investments in R&D

Investments in R&D are often modeled in top-down models. Goulder and Schneider (1999) present a multi-sectoral, top-down general equilibrium model that includes human capital accumulation and intrasectoral spillovers within an intermediate sector. The firm's output X, as shown in equation 6-9, is produced by a CES production function of its knowledge stock H and a composite good G, consisting of capital, labor, energy and materials (KLEM composite). In addition, firms not only benefit from their own human capital stock but also from intrasectoral human capital spillovers ($\bar{H}$). The energy and material inputs consist of carbon and non-carbon energies and of carbon-intensive and non-carbon-intensive materials, respectively. The parameter γ represents a scaling parameter, α and ρ represent distribution and substitution parameters, respectively.

6-9 $$X = \gamma\left(\bar{H}\right)\left(\alpha_H H^{\rho_x} + \alpha_G G^{\rho_x}\right)^{\frac{1}{\rho_x}}$$

The human knowledge stocks, shown in equation 6-10, depend on investments in R&D and do not depreciate. The firm's human capital depends on its own investment in R&D, R_t, whereas the spillover depends on industry-wide R&D efforts $\bar{R}_t$. Investments in R&D are produced by labor as well as the energy and materials mentioned above, ε is a parameter. (Goulder and Schneider 1999, pp. 221-4, Appendix B.3.1.).

6-10 $$\begin{aligned} H_{t+1} &= H_t + \varepsilon R_t \\ \bar{H}_{t+1} &= \bar{H}_t + \varepsilon \bar{R}_t \end{aligned}$$

Goulder and Schneider (1999, pp. 230-4) state that induced technical change increases the responsiveness to a given carbon tax. In addition to substitution away from carbon energy and carbon-intensive materials R&D is re-directed from carbon fuel to non-carbon fuel. They stress that additional opportunity cost result from re-allocating scarce R&D resources but argue, too that benefits rise as well that outweigh the cost, resulting in a net-benefit.

Welsch and Eisenack (2002, p. 492) extend Romer's (1990) growth model of increasing product variety (see section 5.4) in order to analyze the effect of – historically observed – decreasing energy prices on endogenous technical change and on growth. They include energy (E) as an additional factor of production within the Cobb-Douglas production function (i.e. $\alpha+\beta+\gamma=1$) as shown in equation 6-11. Apart from that (and from the notation in continuous time) the equation is similar to equation 5-10.

6-11 $$Y_i = L_i^{\alpha} \cdot E_i^{\beta} \cdot \int_{j=1}^{N} X_{ij}^{\gamma} dj$$

Welsch and Eisenack (2002, pp. 492, 496) show that decreasing energy prices raise the rate of output growth. However, the effect on the rate of technical change, that is, on the growth rate of N, depends on the inverse value of the elasticity of intertemporal substitution η. The household's utility maximization according to the Ramsey model was derived in section 3.4. From that approach one can derive the growth rate of consumption that is shown in equation 6-12. The growth rate of consumption over time depends on the interest rate r, the pure rate of time preference ρ and the inverse value of the elasticity of intertemporal substitution η. The higher η is, the less willing households are to substitute consumption over time. That is, they have a preference for a smooth consumption path, that is, for lower growth rates of consumption.

6-12 $$\frac{\dot{C}}{C} = \frac{r-\rho}{\eta}$$

Welsch and Eisenack (2002, p. 496) show that decreasing energy prices have a negative effect on the growth of knowledge if $\eta > 1$. Decreasing energy prices raise the growth rate of output and consumption. If the 'aversion' against high growth rates in consumption is high enough (i.e. if $\eta > 1$), households decrease savings thus leading to higher consumption now and less consumption growth in the future. However, if households are less avers against high rates in consumption growth (i.e. if $\eta < 1$), the additional resources obtained from decreasing energy cost will also be used to accelerate the growth rate in knowledge yielding higher consumption in later periods thus higher growth rates. A similar reasoning would apply to the case of rising energy prices.

Zon and Yetkiner (2003, p. 83) also modify the Romer (1990) model. In their model, technical change is embodied in the intermediate goods sector. By attaching technical change (i.e. higher energy productivity) to the latest intermediates, they introduce a vintage structure in the intermediate good sector and abandon Romer's symmetry.

The production function, shown in equation 6-13, is similar to equation 5-10 (continuous time) in section 5.4. Final output Y combines labor devoted to final output production L_Y and intermediate inputs x_i^e. (Zon and Yetkiner 2003, p. 86).

6-13 $$Y = L_Y^{1-\alpha} \int_0^A \left(x_i^e\right)^\alpha di$$

The intermediate sector is also described by a Cobb-Douglas technology, as shown in equation 6-14. Employing raw capital x_i and energy e_i, output also depends on the total factor productivity λ_i of that sector. (Zon and Yetkiner 2003, p. 87).

6-14 $$x_i^e = \lambda_i \left(x_i\right)^\beta \left(e_i\right)^{1-\beta}$$

From this specification Zon and Yetkiner (2003, pp. 86, 88) derive the growth rate of λ_i that depends on the total number of intermediates A. This is the key to growth. An increase in the number of intermediates implies a proportional increase in the total factor productivity of the intermediate sector according to the elasticity ς, as shown in equation 6-15. That is, increased R&D output permanently increases the total factor productivity. The parameter ς implicitly measures the quality improvements of the latest intermediate.

6-15 $$\lambda_A = \lambda_0 A^\varsigma$$

It is shown that the unit costs fall with the development of new intermediates. Therefore, growth is stronger than in the original model. Rising energy prices, however, would constitute a counter-acting force that requires a substitution of raw capital for energy. (Zon and Yetkiner 2003, pp. 89-90).

Zon and Yetkiner (2003, p. 98) consider the equilibrium growth effects of an energy tax with and without revenue recycling in the form of a subsidy to the R&D sector. The introduction of an energy tax without an R&D subsidy lowers growth by lowering the net present value of research. With revenue recycling (in the form of subsidizing the research sector), the effect of lower productivity in the research sector is more than offset. However, it does not lead to a bias of technical change towards energy research. They note, however, that energy conservation policies might trigger technical change in applied research that is not captured in the model. As already mentioned in section 5.4, the development of new variants can be perceived as 'break-through'-innovations as opposed to incremental innovations – or applied research – as discussed in section 5.5.

Smulders and de Nooji (2003, pp. 60, 76) develop a model of endogenous and induced innovation that is calibrated in order to match some energy-related stylized facts of the post-war US economy. These are rising energy efficiency and energy per capita, declining energy cost share and declining energy prices in relation to wages. The model also confirms the stylized facts of rising per capita income and a rising fraction of researchers of the total population. The development of per capita energy over time is set exogenously and endogenous technical change explains the declining energy intensity, share and price.

The approach allows for increased variety as well as for increased quality in the intermediate good sector. Therefore, it contains elements of the models of Romer and Schumpeter as discussed in sections 5.4 and 5.5. However, Smulders and de Nooji (2003, p. 63) note that their model relies on in-house research and therefore does not rely on creative destruction. Final output (Y) is produced by a CES production function, as shown in equation 6-16, using labor and energy (resource) services, Y_L and Y_R, respectively. (Smulders and de Nooji 2003, p. 64).

6-16 $$Y = A\left(Y_L^{\frac{(\sigma-1)}{\sigma}} + Y_R^{\frac{(\sigma-1)}{\sigma}} \right)^{\frac{\sigma}{(\sigma-1)}}$$

Input services, in turn, are produced by a Cobb-Douglas/Romer production function (equation 6-17) using the respective raw inputs S_i (i = L, R) and an input-specific intermediate x_{ik} with an associated quality level q_{ik}. The range of intermediates is normalized to one. (Smulders and de Nooji 2003, p. 64).

6-17 $$Y_i = S_i^{\beta} \int_0^1 q_{ik} x_{ik}^{1-\beta} dk$$

Technical change is determined by the change of the quality level over time (denoted by the dot). Equation 6-18 shows that – apart from the scaling coefficient ξ that indicates the productivity of research – the evolution of the quality level depends on the current aggregate quality level Q_i, the firm's in-house investment in R&D (D_{ik}) and sector-wide investment in R&D (D_i). The term 1-ω represents the share of the firm's return to research that spills over to the rest of the sector, meaning that its complement ω represents the share that is appropriable by the firm. (Smulders and de Nooji 2003, p. 68).

$$\text{6-18} \qquad \dot{q}_{ik} = \left[\xi_i Q_i D_i^{1-\omega_i} \right] D_{ik}^{\omega_i}$$

The current aggregate quality level Q_i captures the level of technology. That is, equation 6-18 also implies intertemporal spillovers since the firms build on previous research or knowledge of the sector that they take as given. In a given sector, the rate of growth in quality increases with rising productivity of research, rising aggregate quality level and rising appropriability of research. (Smulders and de Nooji 2003, p. 68)

Maximization of the net present value of the firm yields its optimal investments in R&D. Assuming equal marginal returns on research for all companies, Smulders and de Nooji (2003) derive an expression showing the determinants of the bias of technical change. In addition to rising research productivity and appropriability, also an increasing value share of services of a sector increases the respective rate of quality improvements in that sector over time. (Smulders and de Nooji 2003, pp. 68-9). That is, a larger market (i.e. a higher energy share) leads to a bias of technical change towards that sector. This is in line with the model of Kennedy (1966) discussed in section 4.2.2.1.

Energy conservation policies reduce per capita income levels, which is partially offset by induced technical change. These policies may also lead to a crowding out of non-energy-related R&D, that is induced technical change incurs cost in comparison with the exogenous case where technology falls like 'manna from heaven'. A reduction in the level of energy use accelerates per capita growth because the increased scarcity yields a higher marginal product of energy. A reduction in the growth rate of energy use, however, reduces per capita growth as being a source of growth. (Smulders and de Nooji 2003, pp. 67, 77).

6.3.3 Endogenous Technical Change in RICE/DICE

This section deals with previous attempts to model induced innovation in older versions of the RICE/DICE integrated assessment model family of William Nordhaus and co-authors. RICE consists of several world regions whereas DICE is the aggregated version consisting of one region that contains the whole world. A more detailed description of these models will be given in chapter 7 below when describing the approach of the present work. Attempts to model endogenous growth and/or induced innovation have so far been made in the old model version of RICE and in the DICE-99 model only.

Production and emission relations of the original RICE model of Nordhaus and Yang (1996), referred to as RICE-96, are specified in equations 6-19 and 6-20. Output Q and emission E were originally specified as shown in equation 6-19. Output is produced by a two-factor Cobb-Douglas production function with capital K and labor L. The coefficient A represents the level of technology i.e. total factor productivity. Final output takes into account the (mostly negative) feedbacks of the climate system by the climate damage coefficient Ω and total abatement cost. The latter depend on the abatement cost coefficients, denoted b_1 and b_2, and on the emission control rate μ, that is, the policy parameter. The indices j and t refer to regions and time, respectively.

6-19 $$Q_{j,t} = \Omega_{j,t}\left(1 - b_{1,j,t}\mu_{j,t}^{b_2}\right)A_{j,t}K_{j,t}^{\gamma}L_{j,t}^{1-\gamma}$$

Equation 6-20 shows that emissions depend on gross output, the emissions control rate and the carbon intensity of production σ. In this original specification, exogenous environmental technical progress is represented by the abatement cost b in equation 6-19 and by the carbon intensity σ in equation 6-20. Both coefficients are exogenous parameters that are decreasing over time.

6-20 $$E_{j,t} = \left(1 - \mu_{j,t}\right)\sigma_{j,t}A_{j,t}K_{j,t}^{\gamma}L_{j,t}^{1-\gamma}$$

Nordhaus (2001) modifies the DICE-99 model (R&DICE). Even though DICE-99 is an updated version of DICE, the original specification of production and emission relationships have been left unchanged so that – apart from the regional indices – they are identical to equations 6-19 and 6-20.

In Nordhaus' specification, investment in R&D influences the growth rate of carbon intensity of production. As in the regionalized version, the carbon intensity σ is attached to an exogenous and negative growth rate representing exogenous technical change. This growth rate now depends on the research effort R. As can be seen in equation 6-21, the left hand side represents the (negative) growth rate of carbon intensity. At the right hand side, R represents *current* R&D expenditures. The coefficients are scaling parameters. In this specification, the change in σ is not influenced by an additional capital stock but by current R&D efforts.

6-21 $$\left(\frac{\sigma_t - \sigma_{t-1}}{\sigma_{t-1}}\right) = \phi_1 R_t^{\phi_2} - \phi_3$$

Nordhaus' main result is that emissions reductions from substitution are significantly larger than from induced innovation. Thus, induced innovation plays only a minor role in carbon abatement policies. He attributes this result to the calibration of equation 6-21 reflecting the fact that energy-related R&D in the United States is only 2% of output whereas conventional investments are close to 30% of output. (Nordhaus 2001, pp. 26, 38).

The DICE-99 model is also modified by Popp (2002), who inserts an energy related knowledge stock that influences the use of energy as shown in equation 6-22. Energy increases either due to the increased use of human capital H or due to the increased use of fossil fuels F. In his specification, the current knowledge stock depreciates due to new knowledge rather than due to time. The parameter Φ grows over time representing exogenous technical change.

6-22 $$E_t = \left[H_{E,t}^{\rho} + \left(\frac{F_t}{\Phi_t}\right)^{\rho} \right]^{1/\rho}$$

Introducing scenarios with an optimal carbon tax and with a restriction on emissions on the 1995-levels Popp finds that induced innovation increases welfare. He therefore concludes that omitting induced innovation might overstate the cost of emissions reductions (Popp 2002, pp. 20, 26, 30).

Buonanno et al. (2000a, b, 2001a, b, 2003) modify RICE-96 by modeling investments in R&D that affect output productivity and the emission-output ratio. They introduce a separate research capital stock K_R. This new capital stock accumulates through investments and is subject to depreciation. As can be seen in equations 6-23 and 6-24, a growing research capital stock increases total factor productivity and decreases carbon intensity through investment; α, β and χ are scaling coefficients.

6-23 $$Q_{j,t} = \Omega_{j,t}\left(1-b_{1,j,t}\mu_{j,t}^{b_2}\right)A_{j,t}\left(K_R\right)_{j,t}^{\beta_j}K_{j,t}^{\gamma}L_{j,t}^{1-\gamma}$$

6-24 $$E_{j,t} = \left(1-\mu_{j,t}\right)\left(\sigma_{j,t}+\chi_{j,t}e^{-\alpha_j\left(K_R\right)_{j,t}}\right)A_{j,t}\left(K_R\right)_{j,t}^{\beta_j}K_{j,t}^{\gamma}L_{j,t}^{1-\gamma}$$

Using the Kyoto-forever-scenario[12] as an example, Buonanno et al. (2001b, 2003) conclude that compliance costs are lower with endogenous environment-related technical change. Permit prices are lower, too. This, in turn, leads to lower incentives to carry out R&D. (Buonanno et al. 2001b, pp. 20-4; 2003, pp. 24, 31).

Castelnuovo and Galeotti (2002) build on Buonanno et al. (cp. above) by incorporating a learning curve in the RICE model in a manner that enables a rise in the productivity of physical capital. Equation 6-25 is identical to equation 6-23, except for the second introduction of the conventional capital stock, reflecting installed capacity, with the attached learning-by-doing-coefficient β^L.

6-25 $$\begin{aligned} Q_{j,t} &= \Omega_{j,t}\left(1-b_{1,j,t}\mu_{j,t}^{b_2}\right)A_{j,t}\left[K_{j,t}^{\gamma}L_{j,t}^{1-\gamma}\right]K_{j,t}^{\beta^L} \\ &= \Omega_{j,t}\left(1-b_{1,j,t}\mu_{j,t}^{b_2}\right)A_{j,t}\left[K_{j,t}^{\gamma+\beta^L}L_{j,t}^{1-\gamma}\right] \end{aligned}$$

Enhanced environmental technology is now brought about by physical capital as well, as shown in equation 6-26. Endogenous reductions in carbon intensity are now achieved by conventional capital $K_{j,t}$ instead of research capital.

6-26 $$E_{j,t} = \left(1-\mu_{j,t}\right)\left(\sigma_{j,t}+\chi_{j,t}e^{-\alpha_j\left(K\right)_{j,t}}\right)A_{j,t}\left[K_{j,t}^{\gamma+\beta^L}L_{j,t}^{1-\gamma}\right]$$

Running the Kyoto-forever-scenario, Castelnuovo and Galeotti (2002, pp. 32-3) find that the learning-by-doing-approach is less welfare improving than the R&D-specification. Under the latter, economic agents are able to optimize both conventional and research capital leading to a better ‘distribution of losses’.

12 See section 9.1 for a description of the scenarios.

6.4 Conclusions

In this chapter, several approaches of modeling induced innovation in energy-economic models were presented. They constitute an important progress in comparison with the previous exogenous specifications. However, as Edmonds et al. (2000, p. 18) and Löschel (2002, p. 110) already noted, all these approaches have in common that they rely on some sort of assumption how economic incentives translate into future technologies. This, in turn, means that it is not so much the differences in model types but differences in the assumptions about the model structures (among them: technology) that are the main drivers of results.

Furthermore, the issue of the interplay between restrictions on emissions trading under the Kyoto regime and endogenous technologies have not been addressed. The approach of Buonnano et al (2000, 2001a) is an exception but the use of the old RICE model means that some methodological disadvantages occur. Equations 6-19 and 6-20 show that energy is modeled as a factor of production. Therefore, it is not possible to analyze the bias of technical change towards energy technology, explicitly. The approach that will be described in the next two chapters utilizes the new model version that enables to address this issue.

7 RICE/DICE Integrated Assessment Models

7.1 Introduction

This chapter gives a short introduction to the integrated assessment model RICE-99. A detailed description of the model can be found in Nordhaus and Boyer (2000) as well as in Nordhaus and Boyer (1999b). The latter one is a freely available internet version of the first. The books are virtually identical and the description given in this section refers to the chapters 1-3 if not stated otherwise. The model-code, however, that can be downloaded from the web differs from the description in the book in some important aspects. These aspects affect the modeling of technical change and will be described below.

The code of the model is available in spreadsheet format (Excel) or in GAMS (General Algebraic Modeling System) format. All modeling in the present study has been done using GAMS/CONOPT2. GAMS is a modeling language frequently used by economists that enables the compact representation of large complex models. CONOPT2 is a solver designed for solving non-linear (NLP) programming models[13].

The RICE (**R**egional **I**ntegrated model of **C**limate and the **E**conomy) model family analyses the interactions between climate and the economy. The first aggregated version (DICE, **D**ynamic **I**ntegrated model of **C**limate and the **E**conomy) was described in Nordhaus (1994) and later followed by the regionalized version of Nordhaus and Young (1996), referred to as RICE-96. A major revision of the models that encompasses updates of data as well as major methodological changes has been made at the end of the 1990's. These updated models are known as RICE/DICE-99. RICE-99 runs over 200 years and solves in ten-year-steps. The benchmark year is 1994. That is, it runs from 1994 through 2184.

Being growth models as well as integrated assessment models, the RICE/ DICE models analyse the welfare effects of climate policy in the framework

13 For more technical details on the modeling language the interested reader might refer to www.gams.com

of intertemporal utility maximization according to the theory of optimal savings developed by Ramsey (1928) and described in section 3.4 above.

Technology in RICE-99 is only modeled in an exogenous fashion. Undirected, i.e. Hicks-neutral, technological change increases total factor productivity (see section 3.2 above). In addition, there is technical change that is directed towards carbon productivity, i.e. de-carbonization of the economy. Both will be described shortly.

7.2 Regional Coverage

RICE-99 is a world model consisting of 13 world regions that are shown in Table 7-1. For a more detailed description of the regions the reader may refer to Appendix I. There is no trade in goods between the regions but they are linked through the feedbacks of the climate module as described in section 7.3.3 below. In addition they may exchange emission permits as described in section 7.5 below.

Table 7-1 Aggregated regions in RICE-99.
Source: Nordhaus and Boyer 1999b, ch. 2, pp. 18-9.

Japan	Eastern Europe
USA	Lower-Middle Income Countries (LMI)
OECD Europe	Low Income Countries (LI)
Other High Income Countries (OHI)	China
High Income OPEC (HIO)	India
Middle Income Countries (MI)	Africa
Russia	

In RICE-99, the Annex B countries of the Kyoto Protocol are made up of the world regions Japan, OECD Europe, OHI, Russia and Eastern Europe. Some countries of OHI and Eastern Europe do not belong to Annex B. Emissions are scaled up appropriately.[14]

14 Please refer to section 8.5.2 for the procedure

7.3 Economic Relations

7.3.1 Objective Function

As shown in equation 7-1, a representative agent maximizes welfare W by maximizing discounted money metric utility U. That is, regional per capita consumption c is discounted by the discount factor R, weighted by the regional population L and then aggregated to overall welfare. The indices t and j refer to time and to the RICE world regions, respectively (see Table 7-1). Per capita consumption is an endogenous variable whereas L and R are trend parameters. Initial growth rates for L (taken from U.N. projections) decline over time, leading to a stable population. The representative agents acts under perfect foresight and determines simultaneously the optimal path for the whole model horizon.

7-1 $$W = \sum_{j,t} U_{j,t}\left(c_{j,t}, L_{j,t}\right) \cdot R_t$$

The problems of choosing an appropriate discount rate were already discussed in section 3.4 above. In RICE-99, there is a declining rate of time preference (i.e. ρ in equation 3-6) over time leading to a lower discount factor R and hence higher values attached to benefits in the distant future as compared with constant time preference.

More specifically, the rate of time preference falls from 3% to 2.7% after one hundred years. Therefore, consumption in 2094 is weighted by approximately nine percent in the welfare function as opposed to approximately seven percent with a constant rate of time preference. A more detailed discussion on discounting and climate policy within the DICE-models can be found in Nordhaus (1999). Due to the great uncertainties involved in these long-run projections, model runs and results will be discussed for the first ten periods, that is, for this century only.

RICE is an integrated assessment model meaning that optimization takes into account the (mostly negative) feedbacks of carbon emissions on the economy. The world regions are interconnected through their respective climate vulnerability. Anthropogenic emissions that result from production feed into the climate system of the model. Since the (time-lagged) feedbacks on output are mostly negative, there is a second trade-off between consumption possibilities today and tomorrow. Lower production today means lower associated emissions. These cause lower negative feedbacks and therefore higher production/consumption possibilities in later periods. Thus, anthropogenic GHG emissions become an additional factor that enters intertemporal utility maximization.

7.3.2 *Production and Emissions*

A new treatment of the relationship between production and carbon emissions constitutes a major innovation of RICE-99. Whereas RICE-96 uses a parametric relationship between output and emissions (see Buonano et al. 2001 in section 6.3.3 above), Nordhaus and Boyer (1999b, ch. 1, p. 6 and ch. 3, p. 4) introduce the concept of 'carbon energy' in the new model versions. Carbon energy equals anthropogenic emissions and is a composite of fossil fuels weighted by their carbon content. The advantage of this simplification is that there is no need to specify the substitutional relationships between the different fossil fuels.

As mentioned above, two different published versions of the model exist. In the web-version of the GAMS-code (equation 7-2) carbon energy enters the production function as an additional factor of production. Gross output is produced by a three-factor Cobb-Douglas production function that consists of capital, labor and carbon energy, denoted K, L and E, respectively. Carbon energy is a produced input. Therefore the costs of this factor are subtracted from gross output, leading to the conventional GDP that is known from national accounts. GDP is then adjusted by the climate damage coefficient Ω that will be explained in section 7.3.3 below.

Exogenous technical change that is directed towards energy efficiency is modeled through the output elasticity β. This parametrically decreasing output elasticity leads to a decreasing importance of carbon energy as a factor of production over time. The empirically observed output elasticity of capital (γ) equals 0.3 and the output elasticity of labor is the residual (1-β-γ) meaning that it rises over time. Consequently, the importance of labor as a factor of production increases whereas the importance of energy decreases over time. For a comment on this specification see also Nordhaus and Boyer (1999a). This is the model version, which is available from the web and that is actually used as a starting point for modeling.

7-2 $$Q_{j,t} = \Omega_{j,t} \left(A_{j,t} K_{j,t}^{\gamma} L_{j,t}^{1-\beta_t-\gamma} E_{j,t}^{\beta_t} - c_{j,t}^{E} E_{j,t} \right)$$

The book-version of the model (*not* publicly available in GAMS or spreadsheet format for modeling) comprises another innovation. As shown in equation 7-3, carbon energy is replaced by the production factor energy services ES that enters the production function. The output elasticities are left constant. Carbon energy is adjusted by a ‘carbon augmenting’ technology parameter ς (equation 7-4). According to Nordhaus and Boyer (1999b, ch. 2, pp.16-17), this technology parameter represents the amount of energy services that can be utilized from one unit of carbon energy. This new specification of technical change is factor augmenting as described in section 3.2 above. It is now possible to distinguish between technical change that is directed towards energy efficiency and undirected technical change, i.e. changes in total factor productivity.

7-3 $$Q_{j,t} = \Omega_{j,t}\left(A_{j,t}K_{j,t}^{\gamma}L_{j,t}^{1-\beta_t-\gamma}ES_{j,t}^{\beta_t} - c_{j,t}^{E}ES_{j,t}\right)$$

7-4 $$ES_{j,t} = \varsigma_{j,t}E_{j,t}$$

7-5 $$\varsigma_{j,0} = 1$$

The exogenous technical progress is represented by an exogenous time trend. Starting from unity in the benchmark period (equation 7-5), the parameter (ς) is subject to declining growth rates. The projections are based on historical trends assuming that de-carbonization eventually will decline towards zero. The calibration is adjusted in order to capture the change in emissions that would occur due to changes in the energy mix as a reaction to climate policy. A disaggregated energy model, that takes into account the substitutional relationships between the different fuel sources, has been used to estimate the change in emission due to a 50$ carbon tax.

In both model versions, total factor productivity is subject to decreasing growth rates over time similar to carbon augmenting technical change and population (as mentioned in section 7.3.1 above). It is calibrated in a manner so that per capita output growth slows down in the developed regions. In contrast, total factor productivity growth rates in the developing world do not decrease as much, leading to partial convergence in per capita output growth between developing and developed regions.

The capital stock accumulates to the perpetual inventory model as can be seen in equation 7-6 whereas δ^K is the annual depreciation rate of 10% and I equals annual investment. The equation is adjusted for solving the model in ten-year-steps.

7-6 $$K_{j,t+1} = (1-\delta^K)^{10}K_{j,t} + 10\cdot I_{j,t}$$

Equation 7-7 relates to the supply side of the fossil energy market. The marginal cost of carbon energy c^E depend on three factors: On the current cost of extraction of carbon energy (ξ_1 = 113 \$/t), on a Hotelling rent and on a regional markup that catches regional differences in transportation cost a.s.o. Hotelling rents are scarcity prices that result from the exhaustion of resources (Endres and Querner 2000, p.42).

7-7 $$c_{j,t} = \xi_1 + \xi_2 \left(\frac{CumC_t}{CumC^*} \right)^{\xi_3} + Markup_j^E$$

7-8 $$CumC_t = CumC_{t-1} + 10 \cdot E_t$$

The middle term of 7-7 represents scarcity through the cumulative extraction of carbon energy (CumC, cp. equation 7-8) in relation to the world carbon energy supply (CumC* = 6000 GtC). The parameter ξ_2 equals 700. The parameter ξ_3 equals 4 and implies a highly convex cost function with sharply rising marginal cost once the cumulative extraction passes 3000 GtC of carbon energy.

7.3.3 Linkage between Climate and Economy

GDP is adjusted by the damage coefficient Ω, as seen in equation 7-9, that reflects the (mostly negative) feedbacks from the climate system. That is, Ω smaller than unity lowers output implying damages from climate change and vice versa. The variable T is the increase in average atmospheric temperature with respect to the temperature level from 1900, i.e. before anthropogenic climate change occurred. Equation 7-9 states that there is a relationship between the extent of global warming and the extent of damage resulting from it. This is the central assumption of the model.

7-9 $$\Omega_{j,t} = \frac{1}{\left[1 + \left(\theta_{1,j} T_t + \theta_{2,j} T_t^2\right)\right]}$$

The regional parameters $\theta_{1,j}$ and $\theta_{2,j}$ in equation 7-9 reflect the different impacts of the global change in temperature on the different regions i.e. the respective climate vulnerability. A willingness-to-pay approach has been utilized to estimate the value of preventing future climate change. That is, it estimates the 'insurance premium' that societies are willing to pay in order to avoid future climate change. Studies dealing with the impact of climate change have been used for several categories/sectors including agriculture, sea-level rise and catastrophic events in order to estimate the willingness-to-pay for the different regions. (Nordhaus and Boyer 1999b, chapter 4).

7.4 Climate Module

As already mentioned, RICE-99 is an integrated assessment model that takes into account the dual role of carbon. Being a factor of production on the one hand it contributes to output. Being the main contributor to global warming, on the other hand, it lowers output with a two-period time-lag according to the regions respective climate vulnerability. Rising carbon concentrations in the atmosphere lead to increased radiative forcing. That, in turn, leads to rising temperatures resulting in different feedbacks on the outputs of the different regions.

The design of the climate module in RICE-99 comprises several innovations and updates as compared to the earlier vintage. A three-reservoir carbon-cycle-model has been introduced. Chlorofluorocarbons (CFCs) are now exogenous alongside with updated projections of radiative forcings of other non-carbon green house gases and sulfate cooling, leaving industrial carbon emission as the only endogenous emissions to the model.

7-10 $$E^{Total} = \sum_j \left(E_{j,t} + E_{j,t}^{LUC} \right)$$

Equation 7-10 shows the sum of total regional emissions that enter the climate system. In addition to the regional industrial emissions E, resulting from production, there are regional emissions from land-use change E^{LUC}. The latter ones are exogenous to the model and are calibrated to match current projections from the IPCC and IIASA.

The climate module consist of a three-reservoir carbon cycle model containing the atmosphere, the upper ocean including the biosphere and the deep sea. There is an exchange of carbon between the neighboring reservoirs. That is, a transfer exists between the atmosphere and the upper ocean as well as between the upper ocean and the deep sea but not between the atmosphere and the deep sea directly. This implies a long adjustment time. The exchange rates are expressed as fractions of the mass of carbon of the respective neighboring reservoir. The whole system is calibrated in a manner so that they match existing carbon cycle models and all reservoirs are assumed to be well-mixed in the beginning at pre-industrial levels.

Worldwide emissions from production and land-use change (equation 7-10) enter the atmosphere raising the mass or concentration of carbon in this reservoir with a one-period time lag. The increased stock of carbon increases the transfer to the neighboring upper ocean/biosphere reservoir slowing down the rate of accumulation.

Rising carbon concentration in the atmosphere increases radiative forcings with respect to 1900. They depend on the increase of carbon concentration with respect to pre-industrial levels and other GHG and aerosols. The exact relationship is derived from empirical measurement and climate models. Due to the small fraction of the global warming potential of the other GHG and aerosols and limited scientific knowledge, these are modeled exogenously.

Increased radiative forcings, in turn, increase the average temperature in the atmospheric layer, including the shallow oceans, with respect to the year 1900. The process involves the warming of the deep sea, depends on the difference in temperature between them and involves a one-period time lag. Furthermore, feedback parameters and transfer coefficients reflect the thermal capacities and rate of flows between the reservoirs. This increase in average atmospheric temperature is the variable that finally feeds back into the economy through the climate damage factor in equation 7-9. It affects the regions according to their climate vulnerability as explained in section 7.3.3.

7.5 Emissions Trading

Carbon abatement policy is implemented through the imposition of emission constraints on a group of regions that constitute a trading bloc for emissions trading. The 'allowed' emissions for each region are the result of the international agreed AAUs as discussed in section 2.2.4.1. Equation 7-11 shows the overall cap on emissions of a trading bloc TB and states that the sum of emissions in a trading bloc must not exceed the sum of their assigned amounts.

7-11 $$\sum_{TB \in j} E_{j,t} \leq \sum_{TB \in j} AAU_{j,t}$$

7-12 $$PD_{TB,t} = E_{TB,t} - AAU_{TB,t}$$

7-13 $$Q_{TB,t} = C_{TB,t} + I_{TB,t} + p_t PD_{TB,t}$$

Equations 7-12 defines permit demand of each region of the trading bloc in relation to its assigned amounts, that is, in relation to its emissions target. Permit demand is defined as the emissions that exceed the assigned amounts. A region needs to buy permits from other members of the trading bloc if its actual emissions exceed its assigned amounts. If the region emits less permit demand is negative meaning that the region is a net seller.

Equation 7-13 is a modified regional budget constraint that takes into account the budgetary consequences of emissions trading. Now, output Q has to be allocated not only to consumption C and investment I but also to expenditures on permits (all regional). The latter consist of the permit price p times the amount of permit demand PD. The permit price equals the dual or marginal value of the emissions constraint (equation 7-11). If the region is a net seller the 'negative' expenditures (i.e. its revenue) on permits relax the budget constraint. In order to be in compliance scarce resources have now to be allocated when emissions exceed assigned amounts.

7-14 $$PD_{TB,t} \leq Quota\left(E_{BAU} - AAU_{TB,t}\right)$$

Equation 7-14 introduces restrictions on emissions trading, that is modeled as restrictions on permit demands (trading quota). The quota is exogenously set between zero and unity and determines the amount of emissions trading allowed with respect to domestic action. This specification is in line with Buonanno et al. (cp. section 6.3.3) but there is also an important difference: they set permit demand *equal* to the right hand side of equation 7-14 thereby defining it as a parameter, whereas in the present study permit demand is defined as a variable with an upper bound.

8 Induced Carbon Augmenting Technological Change in RICE-99

8.1 General Approach

Simulation results are only as good as the empirical data that enter the model. Low availability of data is a serious problem especially in the area of environmental innovations. Empirical data that relates to energy-related knowledge and to its effect on energy productivity is barely accessible. In the absence of data, one has to rely on assumptions.

For these reasons, the basic idea is to calibrate the parameters of the extended model (with endogenous investments in energy-related knowledge stocks) in a manner that the variables of the business-as-usual (BAU) projection of the original (exogenous) model are reproduced. As far as possible, other parameters and specifications are left unchanged. One may argue that, in particular with regard to emissions, projections of the IPCC might be more accurate than the ones produced by the rather simple climate module of RICE-99. However, since the current approach represents a modification of an existing model, it seems useful to employ the original as a standard for calibration.

The modeling of technical change that is biased towards a specific factor of production, namely carbon energy, is a major innovation in RICE-99. In the present approach this specification is utilized to integrate induced technical change in a manner that is consistent with endogenous growth. That is, factor augmenting technical change depends on investments and is subject to optimization.

8.2 Endogenous Energy Productivity

De-carbonization has been endogenized by converting the exogenous parameter (ς) into an endogenous variable. The exogenous time trend is replaced by an endogenous index representing the level of energy-related knowledge. For this purpose, the production function of the web-version (that is the one that is actually available for modeling, see equation 7-2) is modified so that it utilizes the concept of energy services of the book-version (see equations 7-3 – 7-5). The time variant output elasticity β that reflects exogenous technical change with respect to carbon energy/emissions in the web-version is set constant to the values of the benchmark period.

As shown in equation 8-1, the newly introduced index describes the level of energy-related knowledge K^E with respect to the benchmark period. The regional coefficient ε represents the elasticity with respect to the growth of energy-related knowledge. That is, it reflects the effect of increased energy knowledge on actual energy productivity. Together these two guide the development of carbon energy productivity or de-carbonization in the economy. In the initial period, the productivity index equals unity and matches the initial value of ς of the exogenous specification (equation 7-5). Thereafter, it grows according to the amount of investments in energy knowledge.

8-1 $$\varsigma_{j,t} = \left(\frac{K^E_{j,t}}{K^E_{j,1}} \right)^{\varepsilon_{j,t}}$$

Energy-related knowledge is modeled as a *stock*, shown in equation 8-2. Analogously to physical capital (equation 7-6), the energy-related knowledge stock accumulates according to the perpetual inventory model through investments I^E. However, the depreciation rate δ^E is set at a lower level (5 %) than for physical capital in order to reflect the human knowledge component (see chapter 5 above).

8-2 $$K^E_{j,t+1} = (1-\delta^E)^{10} K^E_{j,t} + 10 \cdot I^E_{j,t}$$

In the endogenous specification, enhanced energy-related knowledge and associated energy productivity does not come for free any more. As shown in the new regional budget constraint in equation 8-3, output Q has to be allocated to an additional category of expenditure. Investments into the new knowledge stock I^E compete with investments in physical capital I and consumption C. That is, scarce resources have to be invested implying opportunity cost.

8-3 $$Q_{j,t} = C_{j,t} + I_{j,t} + I^E_{j,t}$$

The extension includes an additional strategic variable into optimization. Instead of lowering production itself, economic agents have the means to lower emissions by accelerating the de-carbonization of their economy. Hence, economic agents can diminish the trade-off between production and negative feedbacks from the climate system by investing in energy-related knowledge. On the other hand, there is a new trade-off since investments in energy-related knowledge requires scarce resources on the expenses of consumptions and investments in physical capital. Therefore, the development of sustainable technologies has become subject to cost-benefit considerations.

8.3 Calibration and BAU-Path

8.3.1 Parameter ε and Emissions

As already mentioned, there is no empirical data concerning the effect of increased energy-related knowledge on energy productivity, i.e. concerning ε. In addition, it is not possible to use the exogenous values for ς for calibration since these were not implemented in the web-version (see equation 7-2). Therefore, the elasticity ε is calibrated ‘by hand’ in a trial-and-error process until the regional emissions of the original model are met. That is, there is no automatic algorithm available. The parameter values vary between regions as well as over time (most of them). In order to ensure a smooth development over time, growth rates have been applied to most of the ε’s. In general, the parameters lie between zero and unity (see Appendix II), meaning that there is a concave relationship between the level of K_E and energy productivity[15].

Starting from an arbitrary value of ε between zero and unity the extended model is run leaving the investments into K_E to be determined endogenously. If the resulting emissions in a given region are too high, ε needs to be raised thereby increasing energy productivity and lowering emissions. If emissions are too low, ε needs to be lowered, thus lowering energy productivity and increasing emissions. The values and growth rates for ε are adjusted accordingly and the process is repeated until the original emissions paths are met as closely as possible. The resulting values for ς (starting at unity in the benchmark period) lie between 1.8 in the region HIO and 12.2 in China by the end of the century. These are shown in Appendix II.

15 With the only exception of Japan in the early periods

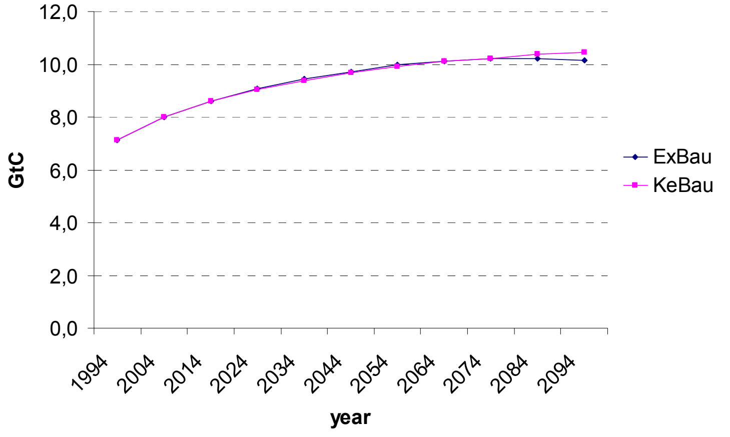

Figure 8-1 Calibrated global carbon emissions.
Source: Nordhaus and Boyer 1999b; own calculations.

Figure 8-1 shows the resulting global BAU emissions path of the calibrated model (KeBau) in comparison with the exogenous BAU-path (ExBau). When there is a trade-off in accuracy between the earlier and the later periods the emphasis is put on the first century due to the uncertainties already mentioned in section 7.3.1 above.

8.3.2 Total Factor Productivity and Output

The extended model exhibits economies of scale leading to higher output, which is a typical feature of endogenous growth models (cp. chapter 5). Inserting the expressions for endogenous energy productivity (equation 8-1) and for energy services (equation 7-4) into the production function (equation 7-3) it is easily shown that the output-elasticities of the three factors do not add up to unity but to $1+\varepsilon\alpha$. The effect is strong enough that it more than compensates the new category of investments I^E.

To accommodate this, the total factor productivities of the regions are re-calibrated using the variables of the original model. That is, the regional variables output Q and emissions E in equation 7-3 as well as investments I and I^E in equations 7-6 and 8-2, respectively, are fixed according to the BAU-paths of the exogenous model (the values for I^E are obtained from the calibration of ε). The fixed investment paths determine the evolution of the capital and knowledge stocks, respectively, and the fixed emissions determine the climate damage. The regional total factor productivities A in equation 7-3, on the other hand, are left as a free variables. Solving the model with this constellation yields the exact productivity required to produce the fixed output with the fixed inputs. The newly obtained values for total factor productivity are then set as parameters and the variables are unfixed again.

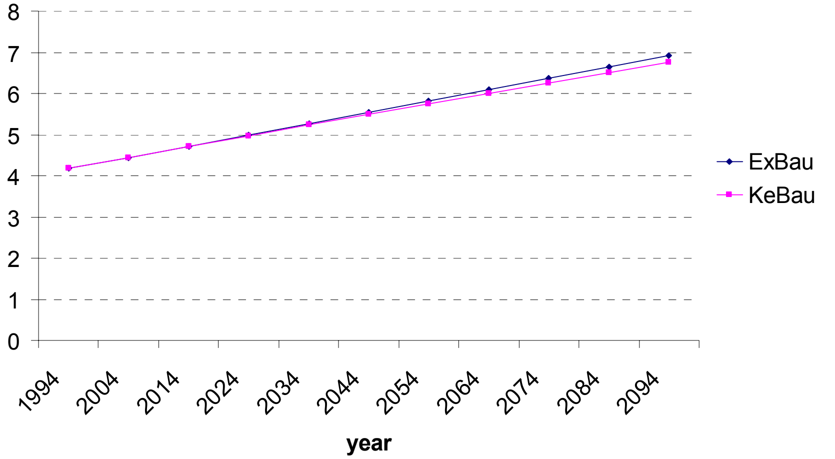

Figure 8-2 Total factor productivity Japan.
Source: Nordhaus and Boyer 1999b; own calculations.

The new total factor productivity develops on a lower path, as shown in Figure 8-2, taking Japan as an example. One can argue that a part of the formerly exogenous and un-directed technical change has now been endogenized as technical change that is directed towards energy productivity, or decarbonization. The new BAU-path reproduces output, consumption and emissions quite well. However, investments in physical capital and the physical capital stock are persistently higher than in the exogenous case.

8.4 Emissions Trading and Endogenous Technical Change

Implementing emissions trading into the extended model is mostly analogous to section 7.5 above. Only equations 7-13 needs to be modified as shown in equation 8-4.

8-4 $$Q_{j,t} = C_{j,t} + I_{j,t} + I^E_{j,t} + p_t PD_{j,t}$$

In fact, equation 8-4 is a combination of the budget constraint as shown in equations 7-13 and 8-3. It contains expenditures on permits as well as investments into the energy-related knowledge stock.

8.5 Empirical Data

8.5.1 Energy-related Knowledge Stock

As already discussed, the lack of empirical data in the field of environmental innovation is a serious problem. To my knowledge, energy-related knowledge stocks are not available in literature.

Therefore, an approximation has been derived. The International Energy Agency (IEA) provides annual data (OECD/IEA 1997, 2000b) on governmental energy-related R&D expenditure from 1974 - 2000 divided by different categories of energy research. Furthermore, the OECD provides data on the gross domestic expenditures on R&D (GERD). These are divided by sector so that the government shares can be used for up-scaling (OECD 1987 - 1998). However, these data are only available for OECD Countries corresponding to the RICE-99 world regions Japan, USA, OECD Europe and OHI (see Table 7-1). The energy-related knowledge stocks for the remaining RICE-99 world regions have to be inferred. The procedure is as follows:

The energy related knowledge stock is built from the categories of fossil fuel related R&D budgets as shown in Table 8-1. More specifically, the categories that are *not* concerned with recovery or exploitation technologies (1.1-1.4, 2.2-2.3, 3.2-3.3, 13.1, see Table 8-1) have been used. Data on renewable energy (Group III) is not considered since the knowledge stock is concerned with the more productive use of fossil energy. From the IEA-database the annual data have been aggregated creating aggregated series from 1974 until 1994 for OECD countries.

Since the resulting time series contain only *governmental* R&D expenditures on fossil fuel related research, it is being scaled up using the OECD time series on the government shares of GERD. For instance, if the government share has been 50 percent in a given year, the figure on the fossil fuel related governmental R&D expenditures has been doubled. Missing data in the time series on government shares have been derived by linear interpolation. Since the series only reach back until 1981, the average percentages have been taken for the early years. The resulting time series represent national annual fossil fuel related R&D expenditures of OECD countries. These are now aggregated according to the RICE-99 world regions mentioned above.

Table 8-1 Categories of energy technology research.
Source: OECD/IEA 1997, pp. 192-6.

Group I Conservation	1.1 Industry 1.2 Residential and Commercial 1.3 Transportation 1.4 Others
Group II Fossil Fuels Production	*2 Oil and Gas* 2.1 Enhanced Oil and Gas 2.2 Refining, Transport and Storage of Oil and Gas 2.3 Oil Shale and Tar Sands 2.4 Others *3 Coal* 3.1 Coal Production, Preparation and Transport 3.2 Coal Combustion 3.3 Coal Conversion (excl. IGCC) 3.4 Others
Group III Renewable Energy Sources	*4 Solar Energy* 4.1 Solar Heating and Cooking 4.2 Photo Electric 4.3 Solar Thermal Electric *5 Wind* *6 Ocean* *7 Biomass* *8 Geothermal Energy* *9 Hydro* 9.1 Large Hydro 9.2 Small Hydro
Group IV Nuclear Fission and Fusion	*10 Nuclear Fission* 10.1 LWR 10.2 Other Converter Reactors 10.3 Fuel Cycle 10.4 Nuclear Supporting Technologies 10.5 Nuclear Breeder *11 Nuclear Fusion*
Group V Power and Storage Technologies	12.1 Electric Power Conversion 12.2 Electric Transmission and Distribution 12.3 Energy Storage
Group VI Other Cross-Cutting Technologies or Research	13.1 Energy System Analysis 13.2 Others

The resulting *regional* time series on annual fossil fuel related R&D expenditures are now used to build up $K^{E}_{j,1}$ for the four RICE regions Japan, USA, OECD Europe and OHI. The data is aggregated according to the perpetual inventory model using an annual depreciation rate of 5%. Due to the long period of twenty years, no initial capital stock is applied. The energy-related knowledge stocks for the remaining regions are inferred by the method proposed by Buonanno et al. (2001b, p. 11). For the four regions, the average ratio of the energy-related knowledge stocks and physical capital stocks is derived for the benchmark year 1994. This ratio and the physical capital stocks of the remaining regions is then used to infer the missing energy-related knowledge stocks shown in Table 8-2.

Table 8-2 Energy-related knowledge stock 1994 by RICE-99 world regions (bill. 1990 US$).
Source: IEA 1997, 2000b; own calculations.

Japan	24,367
USA	22,037
OECD Europe	11,059
Other High Income Countries (OHI)	3,367
High Income OPEC (HIO)	1,249
Middle Income (MI)	4,079
Russia	1,047
Eastern Europe	1,239
Lower-Middle Income Countries (LMI)	3,427
Low Income Countries (LI)	1,443
China	1,724
India	983
Africa	467

The procedure shows that numerous assumptions are used to construct the energy-related knowledge stocks. Especially the derivation for the non-OECD regions imply the same energy-related ‘knowledge intensity’ between the developing and the developed world. This is certainly questionable. Furthermore, one could argue that research on renewable and nuclear energy should be included since both could lead to further de-carbonization. However, the specification in equation 8-1 shows that it is used as an index representing the level of knowledge with respect to the benchmark year. The absolute height of the knowledge has barely an effect on the resulting productivity index. In fact, it is a rather heuristic measure.

8.5.2 1990 Baseline Emissions and Kyoto Commitments

As already mentioned in section 2.2.4 the reduction commitment or targeted emissions are calculated with respect to the emissions of 1990, the so-called emissions baseline. This section describes the derivation of the Kyoto emissions targets for the RICE-99 world regions Japan, USA, OECD Europe, OHI, Russia and Eastern Europe. The resulting emissions targets are shown in Table 8-3. Empirical Data from the Carbon Dioxide Information Analysis Center (CDIAC) is used in RICE-99. Therefore, this source is also used for the derivation of the 1990 emissions baseline and the Kyoto commitments of Annex B in the present study.

CDIAC provides time series of estimated annual carbon emissions for each country from 1751 until today. From the 1990 emissions, the targeted emissions reductions are calculated using the respective emission reduction factors listed in Annex B of the Kyoto Protocol. The country emissions are then aggregated to the RICE-99 world regions. Some regions do not correspond exactly with the Annex B countries so that an adjustment is necessary. Furthermore, some emissions data was not available and had to be derived. The procedures are described below.

Table 8-3 Kyoto emissions targets of Annex B by RICE-99 world regions (GtC).
Source: CDIAC 2001, Kyoto Protocol Annex B, own calculations.

Japan	0.275
USA	1.222
OECD Europe	0.807
Other High Income Countries (OHI)	0.225
Russia	0.733
Eastern Europe	0.526

The RICE-99 world regions OHI and Eastern Europe include some countries that do not belong to the Annex B (see Appendix I). Therefore, the reduction commitment of those regions have been lowered, i.e. the resulting targeted emissions have been scaled up. The respective Kyoto emissions targets of the Annex B countries within OHI and Eastern Europe are calculated and aggregated. An average reduction factor with respect to the aggregated baseline emission of those countries is derived for OHI and Eastern Europe that equals 6% and 3.9%, respectively. This average reduction factor is then weighted with the share of emissions that is represented by the Annex B countries in the regions (86.7% and 91.3%, respectively). This results in reduction factors of 5.4% and 3.6% for OHI and Eastern Europe, respectively.

The baseline emissions of Russia and the countries of Eastern Europe had to be inferred because data on those countries only date back to 1992. Before that time, the Russian Federation, Ukraine, Belarus, Estonia, Lithuania, Moldova and Latvia were aggregated under the former USSR. Furthermore Serbia & Montenegro, Croatia, Slovenia, Macedonia and Bosnia-Herzegovina were aggregated under the former Yugoslavia whereas the Czech Republic and Slovakia constituted the former Czechoslovakia.

For these countries, the 1990 emissions have been derived using the shares of the emissions from 1992 (the 'closest' year available to 1990). That is, the 1992 emissions of the above countries are aggregated to the former states (or union) of USSR, Yugoslavia and Czechoslovakia and the percentage shares from their respective totals are calculated. These shares are then used to derive the baseline from the 1990 emissions of the former USSR, the former Yugoslavia and the former Czechoslovakia.

8.6 Conclusion

This chapter provided the calibration upon which the scenarios will rely. Endogenous investments that are directed towards energy productivity have been implemented into the model RICE-99. Therefore, induced factor augmenting technical change that is directed towards de-carbonization of the economy is now subject to economic optimization of the economic agents. Furthermore, the Kyoto emissions baseline and a trading bloc that resembles the Annex B regions is implemented. It is now possible to study the interrelations between the flexibility of emissions trading and the development of endogenous energy-saving technology.

9 Scenarios and Results

9.1 Introduction

Model-based scenarios have to rely on numerous assumptions. In addition to these insecurities, finite time horizon models imply a sudden fall in investments at the end of the model horizon. This is partially offset by terminal conditions[16]. However, some problems remain. Due to the uncertainties mentioned earlier results are only shown for the first century whereas model runs are performed for 200 years. Despite these insecurities, some qualitative conclusions can be drawn.

There are three cases. A Kyoto forever case (KyEv), a Kyoto dynamic case (KyDyn) and a case that restricts atmospheric concentration of CO_2 to 500 ppm. Each case is run with four different degrees of emissions trading: 100%, 75%, 50% and 25%. Therefore, apart from the BAU-scenario, we arrive at 12 scenarios (see Table 9-1). All figures in this chapter show the variables as %-deviations from BAU-variables.

Table 9-1 Scenarios.

Bau	Business-as-usual
KyEv100	Kyoto forever, 100% Annex B -ET
KyEv75	Kyoto forever, 75% Annex B –ET
KyEv50	Kyoto forever, 50% Annex B –ET
KyEv25	Kyoto forever, 25% Annex B –ET
KyDyn100	Kyoto dynamic, 5% reduct. per decade, 100% Annex B -ET
KyDyn75	Kyoto dynamic, 5% reduct. per decade, 75% Annex B -ET
KyDyn50	Kyoto dynamic, 5% reduct. per decade, 50% Annex B -ET
KyDyn25	Kyoto dynamic, 5% reduct. per decade, 25% Annex B -ET
500ppm100	Concentration target: 500 ppm, equal burden sharing, 100% global ET
500ppm75	Concentration target: 500 ppm, equal burden sharing, 75% global ET
500ppm50	Concentration target: 500 ppm, equal burden sharing, 50% global ET
500ppm25	Concentration target: 500 ppm, equal burden sharing, 25% global ET

16 See Lau et al. (1997) for modeling terminal conditions.

All cases have in common that they start with the Annex B emission targets and Annex B emissions trading without the US in 2014. That is, they start with the Marrakech Accord (see section 2.2.3). Due to the commitment reserve and the reporting and monitoring procedure of the GHG inventories, emissions trading on a larger scale will only begin at the end of the first commitment period, that is 2012, or even thereafter (see section 2.2.4.1). Since the model solves in ten-year steps with the benchmark period in 1994, compliance and Annex B emissions trading (without the US) in all scenarios start in 2014. A basic assumption of all scenarios is that the US will re-join the climate change community in the second commitment period. That is, the US will comply with their respective targets and join the trading bloc in 2024.

In the Kyoto forever case (KyEv%), the Annex B regions Japan, OECD Europe, OHI, Russia and Eastern Europe comply with their Kyoto targets and start Annex B emissions trading in 2014, i.e. in the first commitment period. These targets remain for the whole time horizon of the model. Similarly, in 2024 (the second commitment period) the US complies with their Kyoto target and joins emissions trading as well for the rest of the time horizon.

In the Kyoto dynamic case (KyDyn%), the Annex B-regions (without the US) reduce their emissions by 5% per decade with respect to their Kyoto targets, starting after the Marrakech Accord in the second commitment period. That is, in 2024, their target is 95% of the Kyoto emissions; in 2034, it is 90% a. s. o. The US complies with the same dynamic commitment, lagging one decade behind. That is, in 2024, when the Annex B already reduce their targeted emissions by 5% with respect to the Kyoto target, the US are committed to their Kyoto target and start the same reductions thereafter.

In the 500 ppm case (500ppm%), all remaining world regions (including the US) join Annex B trading bloc after the Marrakech Accord in the second commitment period, thus creating worldwide emissions trading. Equal burden sharing is assumed for all regions. That is, all world regions have to reduce their emissions by the same percentage with respect to their BAU-paths that is necessary to maintain the concentration target. The necessary percentage emission reduction was obtained from an earlier model run with an upper bound on the atmospheric concentration in the climate module. If the resulting emissions targets are higher than the Kyoto targets, the Annex B regions stick to their Kyoto commitment until the concentration target requires further reductions. The exception, again, is the US who is assumed not to be committed to the Kyoto targets but only to the equal burden sharing.

9.2 Kyoto Forever Case

The regional emission targets are binding for Japan and OECD Europe only until 2034 whereas for Russia and Eastern Europe it is not binding at all (hot air, see section 2.2.4.1). For OHI, the target remains binding throughout the whole century and once the US joins the trading bloc, its target remains binding throughout the whole century as well.

Due to the hot air and falling BAU-emissions in some regions over time, restrictions on emissions trading lower total Annex B emissions and lower permit prices. The reason is that restrictions on emissions trading restrict the availability of abundant permits (hot air) from Russia and Eastern Europe for the permit demanding regions (mainly OHI and the US). In the event of restricted emissions trading, these regions cannot comply by simply buying permits but have to take domestic action. That is, they have to invest in energy productivity and/or reduce emissions.

In scenario KyEv100 in 2014, Japan, OECD Europe and OHI have to comply with their regional targets and buy permits from Russia and Eastern Europe. When the US enters the trading bloc in 2024, it becomes by far the biggest demander of permits and together with OHI they remain net demanders throughout the whole century. Japan and OECD Europe reverse their role in 2024 and – together with Russia and Eastern Europe – become net sellers of permits for the rest of the century. All other Annex B parties except the US and OHI now raise their investments in energy productivity and lower their emissions in order to sell permits to the US and OHI.

In 2014, restrictions on emissions trading (i.e. in the scenarios KyEv75, KyEv50 and KyEv25) trigger additional investments in energy productivity as a substitute for permit purchases, and lower emissions in Japan, OECD Europe and OHI. In 2024, these restrictions have the same productivity-increasing and emissions-lowering effect on the US. In Russia and Eastern Europe, restrictions on emissions trading restrict the volume of possible sales, therefore lowering additional investments in energy productivity and leading to fewer emission abatement. Japan and OECD Europe – being net buyers at first – also increase their energy productivity and lower their emissions. When they become net seller in 2024, they reduce their investments in energy productivity and abate fewer emissions in comparison to KyEv100.

As long as all regional targets are binding, they trigger additional investments in energy R&D, resulting in higher energy productivities in all regions taking part in the trading bloc. If some of the regional emissions targets are not binding anymore (due to falling BAU-emissions over time), investments in energy productivity fall back to BAU-levels in *all* regions when there is full emissions trading (KyEv100). This is also true for the US and OHI because they can comply with their (still binding) regional targets via the purchase of permits instead of raising their energy productivity and/or lowering emissions (Figure 9-1). Restrictions on emissions trading result in persistently higher investments in energy productivity in these permit-demanding regions, whereas in the permit-selling regions, restrictions on emissions trading lead to less additional investments in energy productivity and less additional abatement.

Japan, OECD Europe and the US benefit from less climate damage due to reduced emissions. Their climate damage coefficient (Ω, see equations 7-3 and 7-9) decreases less when the quota on emissions trading is stricter, leading to values above BAU-levels (Figure 9-3) and to smaller losses in output and consumption. In KyEv25 these smaller losses and the restricted possibility (or obligation) to sell permits to the US and OHI even lead to a fall of investments in energy productivity persistently below BAU-levels (Figure 9-2) and a rise of emissions persistently above BAU-levels in Japan and OECD Europe. Even though the US benefits from a slight climate change (i.e. the climate damage coefficient is greater than unity), their climate damage coefficient starts decreasing already from 2024 on, so that they also benefit from the emission reductions. These gains from abated climate change also show in some regions of the non-Annex B world.

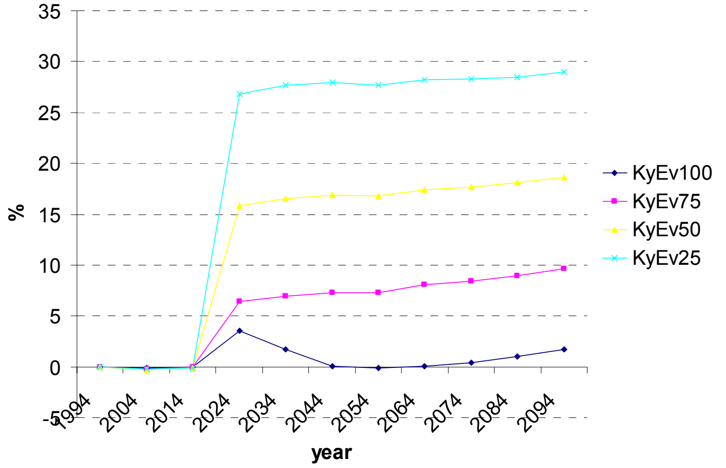

Figure 9-1 Deviation from BAU-energy productivity, Kyoto forever case, USA.

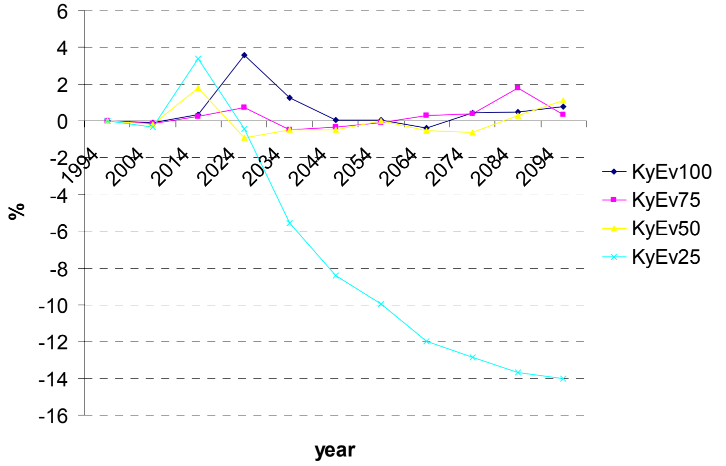

Figure 9-2 Deviation from BAU-energy productivity, Kyoto forever case, OECD Europe.

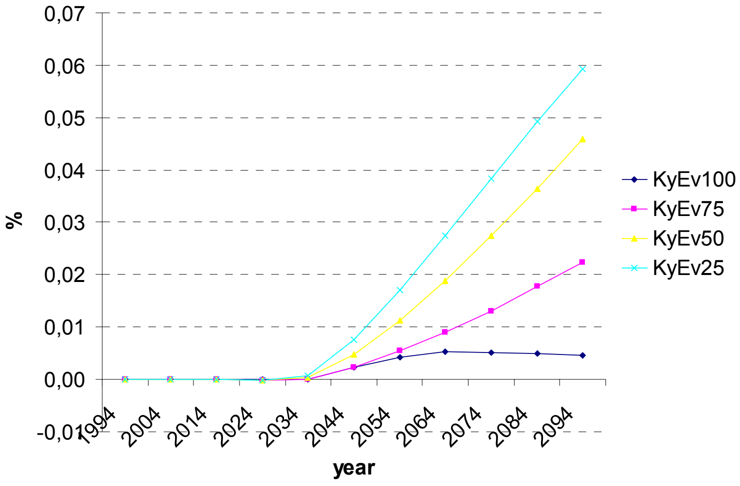

Figure 9-3 Deviation from BAU-climate damage coefficient, Kyoto forever case, OECD Europe.

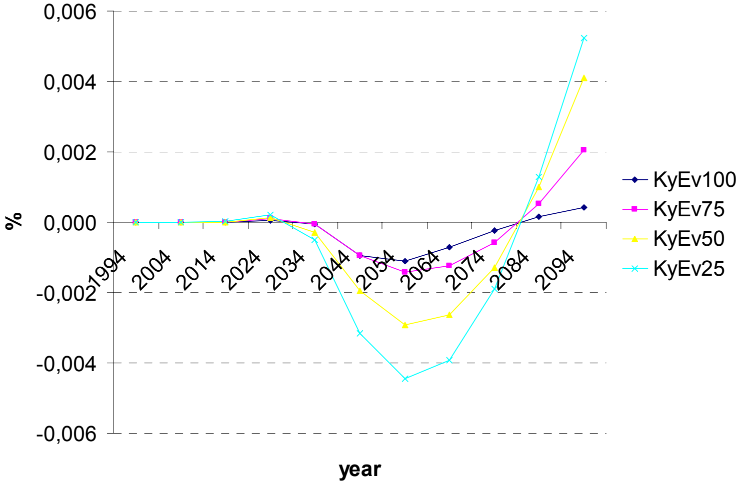

Figure 9-4 Deviation from BAU-climate damage coefficient, Kyoto forever case, Russia.

OHI, Russia (see Figure 9-4) and Eastern Europe are affected negatively by the emissions reductions in the first half of the century because they benefit from climate change up to a certain degree. But in the second half of the century, they would also be affected negatively from the increasing climate change. Therefore, these regions also benefit from emissions reductions in the second half of the century.

In Japan and OECD Europe, restrictions on emissions trading result in lower contributions to the abatement of the US and OHI and to less damage from climate change both leading to higher output and consumption/welfare. In the US, the positive effect from less climate damage is overcompensated by the cost of increased domestic action in the event of restricted emissions trading whereas in OHI the cost of increased domestic action and less climate change both lower consumption/welfare. In Russia and Eastern Europe, the costs and benefits from restricted emissions trading roughly cancel out. Some non-Annex B regions benefit from the environmental effects of restricting emissions trading resulting in higher consumption/welfare.

9.3 Kyoto Dynamic Case

Like the Kyoto forever case, this case starts out with the Marrakech Accords in 2014, meaning that the US do not join the trading bloc before the second commitment period in 2024 (see sections 2.2.3 and 9.1). Due to hot air, restrictions on emissions trading lower the Annex B emissions and permit prices in the first half of the century but the effect later vanishes due to more stringent new commitments. The scenarios KyDyn100 and KyDyn75 trigger almost identical permit demands meaning that possible permit demands are not fully used in KyDyn100. Due to the new commitment, the regional emission targets are now binding for Annex B throughout the whole century except for Russia and Eastern Europe, who are still not restricted. Once the overall target becomes binding, it remains that way throughout the whole century and triggers persistently higher investments in energy productivity in the whole Annex B.

In 2014, we have the same situation as in the Kyoto forever case with Japan, OECD Europe and OHI having to comply with their regional targets and purchasing permits from Russia and Eastern Europe. Like before, the US becomes the biggest demander of permits in all scenarios when entering the trading bloc in 2024. In the scenarios KyDyn100 and KyDyn75 Japan and OECD Europe also become net sellers of permits accompanied by further increasing energy productivities and further decreasing emissions. Similarly, restrictions on emissions trading trigger additional investments in energy productivity and lower emissions in the permit demanding regions.

When the US enter the trading bloc in 2024, its investments in energy productivity remain persistently higher and emissions remain persistently lower than BAU-levels, even in the presence of full emissions trading (KyDyn100). That is, due to the more ambitious commitment, there is less hot air available and parties have to prepare for the commitments to come. Restrictions on emissions trading further raise investments in energy productivity, as shown in Figure 9-5, and further lower emissions in the US because, like before, the US has to rely more on domestic action.

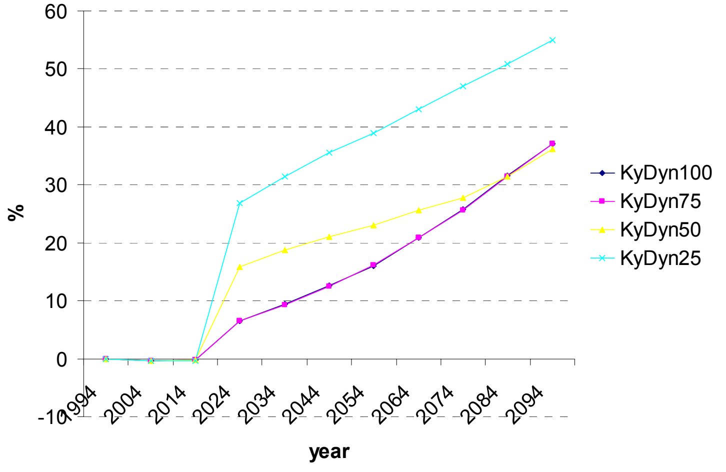

Figure 9-5 Deviation from BAU-energy productivity, Kyoto dynamic case, USA.

In KyDyn50, Japan and OECD Europe remain net demanders of permits until 2034 and in KyDyn25 even throughout most of the century. This goes along with lower additional investments in energy productivity (Figure 9-6) and lower additional abatement. Here, too, the reason is that these two regions cannot contribute as much to the effort of the US and OHI through permit sales. Instead, in KyDyn25, Japan and OECD Europe even sometimes buy permits from Russia and Eastern Europe, because restricting emissions trading lowers permit prices. Nevertheless, due to the more stringent targets energy productivities remain above BAU-levels.

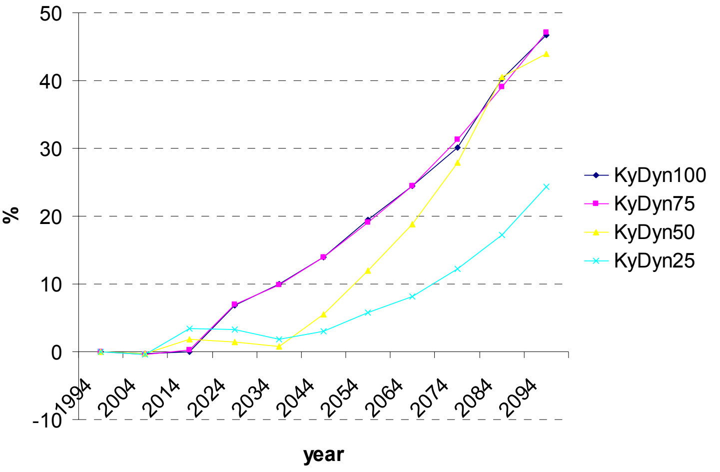

Figure 9-6 Deviation from BAU-energy productivity, Kyoto dynamic case, OECD Europe.

As already mentioned, the Kyoto dynamic case leads to persistently higher investments in energy productivity in all scenarios in the whole Annex B. Restrictions on emissions trading trigger *further* additional investments in energy productivity (Figure 9-5) and additional abatement in the US and in OHI who are net demanders of permits. In Japan and OECD Europe, restrictions on emissions trading lower additional investments and abatement because they cannot sell as many permits. By the end of the century/beginning of the next century energy productivities go back to the levels of the scenario with full emissions trading. That is, the additional increase in productivity due to the restrictions on emissions trading is only temporary. However, this lasts for the whole century (KyDyn50) or even longer (KyDyn25).

In the Kyoto dynamic case, the regions are affected by climate change in the same manner as in the Kyoto forever case but with higher magnitude, due to the greater emissions reductions. Japan, OECD Europe and the US benefit from less climate damage. OHI, Russia and Eastern Europe only benefit in the second half of the century from the reductions because they would have benefited from climate change at first. Again, these gains from abated climate change also show in some regions of the non-Annex B world.

In the Kyoto dynamic case, the emissions target is more ambitious and leads to higher gross costs. However, like in the Kyoto forever case, Japan, OECD Europe, Russia and Eastern Europe benefit from restrictions on emissions trading because restrictions result in lower contributions to the overall emissions target. The higher costs also overcompensate the benefits from climate change in Japan, OECD Europe and the US. The US and OHI both lose from restricted emissions trading because they have to increase domestic action. OHI also loses from abated climate change in the first half of the century. Like in the Kyoto forever case, Russia and Eastern Europe both lose from abated climate change in the first half of the century, overcompensating the benefits from restricted emissions trading. In the Kyoto dynamic case, too, some non-Annex B regions benefit from the environmental effects of restricting emissions trading.

9.4 500 ppm Case

The 500 ppm case triggers quite different reactions as compared to the Kyoto cases. When the rest of the world complies with its targets and starts global emissions trading after the Marrakech Accord in 2024, the regional emissions targets are binding for *all* world regions. That is, there is no hot air available any more. The reason is that, due to the equal burden sharing, the targets are calculated as percentage reductions from the projected *BAU*-emissions and result in large drops of targeted emissions in Russia and Eastern Europe. Furthermore, restrictions on emissions trading have no effect on overall emissions or permit prices.

The required abatement for OHI is not as stringent as the Kyoto target in the first half of the century. During that time, OHI sticks to the Kyoto commitment as already mentioned in section 9.1. Therefore, restrictions on emissions trading do have some small effects on regional emissions and energy productivities in the first half of the century. Still, the regional emissions targets are binding for all world regions from 2024 on and there is no hot air either.

Under the global regime after 2014, the US, after being a net seller at first, becomes a net demander in 2054 with constantly increasing demands. OECD Europe remains a net buyer until 2064. The main sellers are Japan and China from 2024 and 2034 on, respectively. LMI, LI and India are all net demanders in the first half of the century before they turn into net buyers. OHI's initial high permit demand – when not restricted – constantly falls until 2064 when the target of the concentration scenario requires greater reductions than the Kyoto target.

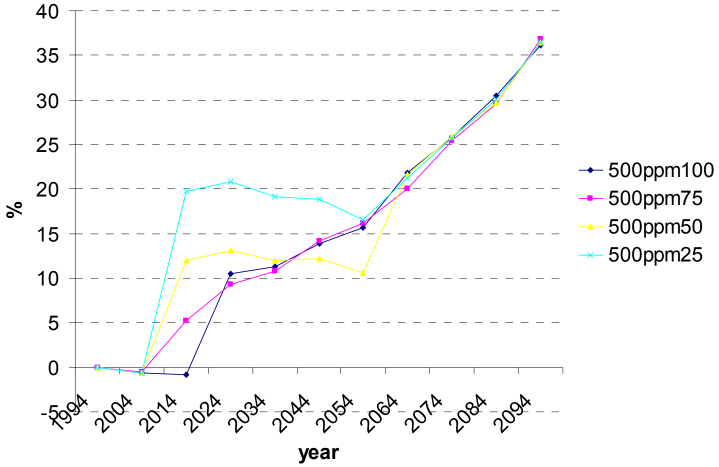

Figure 9-7 Deviation from BAU-energy productivity, 500 ppm case, OHI.

The fact, that the target for OHI under the Kyoto regime is more stringent than under the 500 ppm case in the first half of the century, violates the equal burden sharing principle. Emissions trading provides the means to distribute this additional burden among the other regions via the purchase of permits. Japan and OECD Europe increase their permit sales and LI, China, India and Africa lower their permit demands. All of them increase their energy productivities and lower their emissions. However, the effects are small. In this situation, restrictions on emissions trading force OHI to increased domestic action by increasing energy productivity (Figure 9-7) and lowering emissions, whereas the others lower their efforts due to the restricted possibility to contribute to it via emissions trading.

The 500 ppm case triggers persistently higher investments in energy productivity in all world regions. Interestingly, the highest increases with respect to the BAU-levels are found in the Annex B, ranging from 35% (OHI) to 80%

(Japan). In the non-Annex B world, these figures range from 2% (Africa) to 30% (China). Restrictions on emissions trading matter as long as OHI sticks to the Kyoto commitment and the equal burden sharing rule is violated. In this situation, restrictions on emissions trading require additional investments in energy productivity and lower emissions (see Figure 9-7). The contributing regions lower their efforts, when emissions trading is restricted. Once OHI sticks to the equal burden sharing, energy productivities are virtually the same in all scenarios, regardless of restrictions on emissions trading.

All regions except OHI, Russia and Eastern Europe benefit from climate change. OHI loses benefits that would have occurred from climate change during 2044 – 2064 before it also gains from the environmental policies. Russia and Eastern Europe lose from 2044 until 2074 and 2054, respectively. Here too, restrictions on emissions trading have no effect.

Almost all regions lose welfare because the gross cost of emissions reductions outweigh the benefits from abated climate change in the first century, resulting in lower consumption during that time. Decreasing losses or net increases in consumption with respect to BAU-levels occur only in the next century. The exception is OECD Europe, where consumption rises above the BAU-level already in 2064.

9.5 Discussion

9.5.1 Review

In the Kyoto cases, restrictions on emissions trading have two effects: they affect the regional contributions to the overall emissions target and – due the presence of hot air – the changing emissions affect the regions according to their climate vulnerability. Both effects influence investments in energy R&D and associated energy productivities.

When emissions trading in the Kyoto cases are restricted, the buyer regions USA and OHI significantly raise their carbon efficiency whereas the sellers Russia and Eastern Europe as well as OECD Europe reduce it. The logic behind this result is evident: Buyers have to switch to domestic action to fulfill their abatement obligations and therefore raise carbon-saving R&D. On the other hand, sellers now are confronted with a smaller market. This scale effect reduces their incentive to undertake R&D.

Restricting Trade in the presence of hot air also implies a special kind of leakage effect depending on the climate vulnerability of the respective region: if a region suffers from climate change (that is, the climate damage coefficient decreases), it benefits from the emissions reductions that result from restricted emissions trading, thus enhancing output and consumption. If those regions face no carbon obligation (i.e., the non-Annex B regions in the Kyoto cases), their investments in carbon productivity is below BAU-levels.

The 500 ppm case comprises elements of the Kyoto cases as long as OHI's Kyoto commitment violates the equal burden sharing principle. As long as OHI takes an additional burden by sticking to the Kyoto commitment, restrictions on emissions trading have similar effects on energy productivities and regional (but not overall) emissions as in the Kyoto cases. OHI, as a net demander of permits, loses access to comparably cheap abatement when emissions trading is restricted, leading to higher energy productivity, lower emissions and to consumption losses.

Once the 500 ppm commitment gets more stringent than the Kyoto commitment for OHI as well, the absolute amount of permit demand and overall emissions do not change when emissions trading is restricted. The volume of trade is so low that the quotas are not binding. The reason is that the emissions targets are closer to the least-cost allocation of permits. Therefore, there are no 'corner solutions' like under the Kyoto constellation in the sense that only a part of the trading bloc faces a binding emissions target and that these regions can comply by the reception of abundant permits from regions that do not have binding targets. Once the restrictions are not binding in the 500 ppm case, they have no effect on energy productivities either.

9.5.2 When Do Restrictions Matter?

Restrictions on emissions trading tend to have no effect when there is equal burden sharing. They affect energy productivities and regional emissions when there is unequal burden sharing. In the presence of hot air (an extreme form of unequal burden sharing), restrictions on emissions trading also lower *overall* emissions so that, in turn, climate is affected, too.

Therefore, restrictions on emissions trading influence the distribution of abatement (i.e. burden sharing) among the regions and the amount of climate damage in the Kyoto constellation. Net buyers, namely the US and OHI, cannot comply simply by the purchase of permits but have to lower emissions and raise investments in energy R&D. Net sellers, in turn, are confronted with a smaller market when emissions trading is restricted and decrease their additional efforts in terms of energy productivity. Thus, in the Kyoto forever (dynamic) case, restricted emissions trading leads to more (additional) investment in energy R&D in net buying regions and to less (additional) investment in energy R&D in net selling regions.

In addition, the emissions lowering effect sometimes leads to investments in energy R&D below BAU-levels in some regions (free riding). Therefore, the notion that restrictions on emissions trading are needed in order to enhance the transition towards a low carbon trajectory is not always correct in the current modeling framework.

9.5.3 Effect on per Capita Consumption

In terms of global welfare (or per capita consumption paths in order to avoid discount rate considerations), restrictions on emissions trading have virtually no effects compared to the case of full emissions trading. On a regional scale, effects on consumption do in some regions – but not all – depend on the admissible degree of ET. Permit demanding regions tend to lose whereas permit selling regions tend to gain from the restrictions on emissions trading.

On a world-wide scale we find that KyEv has practically no impact on consumption. This holds irrespective of the degree of emissions trading, which suggests that the economic costs of trade restrictions are just offset by the more pronounced reduction of climate damage when trade is restricted. In the KyDyn and 500ppm cases we find small reductions of global consumption but even in these cases the degree of admissible emissions trading has virtually no influence. This is due to the fact that the global carbon trajectories differ less between full emissions trading and restricted emissions trading than under KyEv (less ‘hot air’).

On a regional scale, effects on consumption do in some regions – but not all – depend on the admissible degree of emissions trading. Under KyEv the permit selling regions Russia, Eastern Europe, OECD Europe (Figure 9-8), and Japan tend to benefit somewhat from trade restrictions while the permit buyers US (Figure 9-9) and OHI incur a loss. Thus, the enhanced decarbonization in permit buying regions tends to be a poor substitute for the possibility to purchase carbon abatement from abroad. Most non-Annex B regions benefit from trade restrictions due to reduced climate damage. In the KyDyn and 500ppm case trade restrictions have little impact on regional consumption.

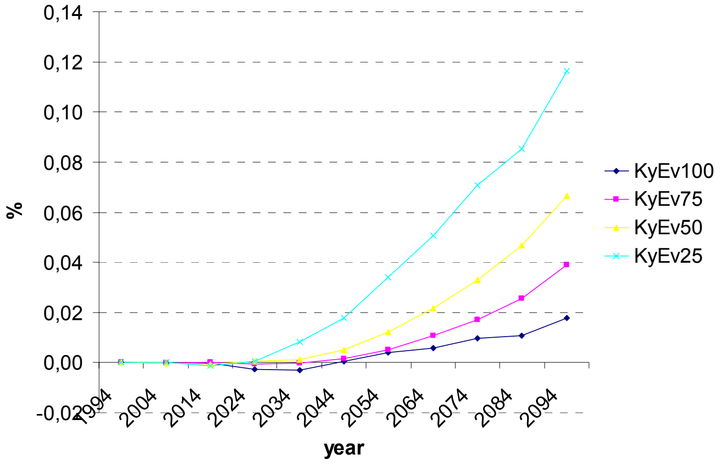

Figure 9-8: Deviation from BAU-per capita consumption, Kyoto dynamic case, OECD Europe.

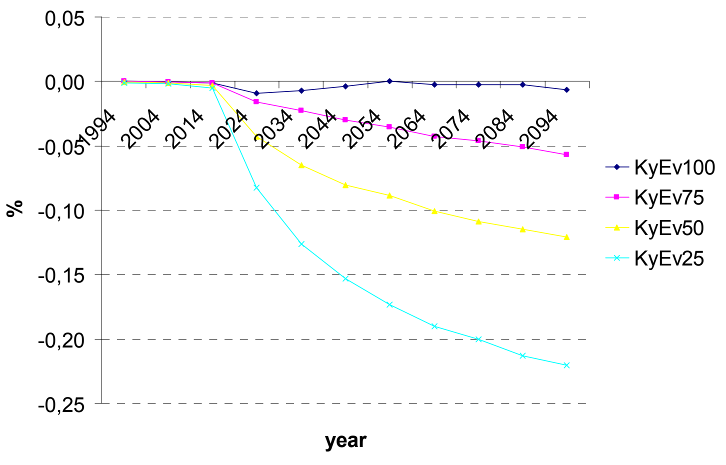

Figure 9-9: Deviation from BAU-per capita consumption, Kyoto dynamic case, USA.

10 Summary and Conclusions

The current work has analyzed the effects of restricting international emissions trading on endogenous energy-saving innovation. The integrated assessment model RICE-99 has been modified in order to include endogenous technical change. This version of the RICE/DICE model family comprises distinct methodological innovations concerning production and emission relations. These allow to model endogenous technical change that is directed towards energy, or carbon productivity in a "factor augmenting" formulation known from endogenous or "new" growth theory.

This approach constitutes an innovation when compared with previous endogenous specifications of technical change. Investments in an energy-related knowledge stock increase the carbon productivity in production and are subject to optimization. The model is calibrated so that it reproduces the BAU-variables of the original model with exogenous technical change. Simulations have been made with various emissions commitments and with various restrictions on flexibility, that is, with quotas on emissions trading.

The significance of restricted flexibility for the acceleration of energy-saving technical change depends on the burden sharing regime. In the case of equal burden sharing, they tend to have no effect because of the small amount of emissions trade under this regime. When burden sharing is unequal, restrictions on emissions trading lead to higher energy productivities in permit demanding regions, but to lower additional energy productivity in net selling regions. Thus permit demand and energy R&D act as substitutes.

There is a trade-off between allocation and distribution. Restrictions on emissions trading lead only to small additional losses in *overall* welfare but they have different effects on *regional* welfare. In terms of per capita consumption, permit demanding regions lose and permit supplying regions gain from restrictions. Restrictions on emissions trading place an additional burden on net demanders and vice versa and therefore are valued quite differently from the different regional perspectives.

In the Kyoto scenarios that involve 'hot air', restricted flexibility leads to a particular type of leakage effect in countries without abatement commitment: Restrictions on emissions trading lower *overall* emissions that results in reduced climate damage for most regions. Reduced damage, in turn, raises emissions and reduce investments in carbon productivity in those countries. In some cases this is also true for net selling regions under a commitment, when flexibility is very low.

The conclusions have been obtained in a framework of costly R&D. It is an open question whether results that are more in favor of trade restrictions would be obtained in a learning-by-doing-model. In reality, both types of technical progress might be at work simultaneously.

In addition, the conclusions are subject to the limitations of the model and the methodological approach in general. The intertemporal model derives an 'optimal' path because it assumes perfect foresight, market clearance and a number of additional assumptions regarding the discount rate, the future development concerning the population, autonomous technical progress, total factor productivity a. s. o. However, some qualitative conclusions could be drawn that hold in the light of many conceivable parameter constellations and might clarify some points of the debate.

Overall, it may be concluded that the debate on whether or not to restrict the trade in carbon permits in the presence of induced carbon saving technological progress is difficult to settle on efficiency grounds. Trade restrictions mainly induce a reallocation of R&D efforts among buyers and sellers and a small shift of welfare from the former to the latter, but the worldwide welfare effects are almost invisible. Thus, the issue seems to be largely of a distributional or political nature with little implications for global welfare.

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Appendix I
Regional Details of the RICE-99 Model.

Source: Nordhaus and Boyer 1999, Table 3-1.

	Industrial CO2 emission	Gross Domestic Product (1990 U.S. prices, market exhange rates)		Population	CO2-GDP Ratio
	(1000 tons of carbon) 1995	($billions) 1995	GDP growth rate 1970-1995	(millions) 1995	(tons carbon per $thousand) 1995
United States	1,407,257	6,176	2,6	263,12	0,23
Other High Income	556,855	4,507	3,6	191,61	0,12
Japan	307,520	3,420	3,6	125,21	0,09
Canada	118,927	541	3,2	29,61	0,22
Australia	79,096	295	3,1	18,05	0,27
Singapore	17,377	46	8,1	2,99	0,38
Israel	12,642	66	5	5,52	0,19
Hong Kong	8,459	84	7,4	6,19	0,1
New Zealand	7,489	49	2,2	3,6	0,15
Virgin Islands (U,S)	3,121	2	NA	0,1	2,01
Guam	1,129	,,	NA	..	NA
Aruba	491	,,	NA	..	NA
Bahamas	466	3	NA	0,28	0,14
Bermuda	124	1	NA	0,06	0,08
British Virgin Islands	14	,,	NA	..	NA
Andorra	,,	,,	NA	..	NA
Faeroe Islands	,,	,,	NA	..	NA
Monaco	,,	,,	NA	..	NA
San Marino	,,	,,	NA	..	NA
OECD Europe	850,839	6,892	2,4	380,85	0,12
Germany	227,920	1,787	2,3	81,87	0,13
United Kingdom	147,964	892	2,1	58,53	0,17
Italy	118,927	998	2,6	57,2	0,12
France	92,818	1,189	2,5	58,06	0,08
Spain	63,211	406	2,9	39,2	0,16
Netherlands	37,093	303	2,4	15,46	0,12
Belgium	28,334	189	2,3	10,15	0,15
Greece	20,820	60	2,5	10,47	0,35
Norway	19,774	125	3,5	4,35	0,16
Austria	16,179	165	2,7	5,11	0,1
Denmark	14,975	132	2,1	5,22	0,11
Portugal	14,172	58	3,3	9,93	0,24
Finland	13,923	107	2,4	5,11	0,13
Sweden	12,170	195	1,6	8,83	0,06
Switzerland	10,604	213	1,4	7,04	0,05
Ireland	8,798	53	4,2	3,59	0,16
Luxembourg	2,528	13	NA	0,41	0,2
Iceland	492	6	NA	0,27	0,08
Greenland	137	1	NA	0,06	NA
Liechtenstein	,,	,,	NA	..	NA

Russia and Eastern Europe	863,849	1,095	1,6	535,09	0,79
Russia	496,182	334	1,2	148,2	1,48
Eastern Europe	367,667	380	2,8	193	0,95
Ukraine	119,599	34	1	51,55	3,55
Poland	92,818	74	NA	38,61	1,25
Romania	33,049	35	NA	22,69	0,95
Czech Republic	30,581	37	10,9	10,33	0,83
Belarus	16,185	20	1,2	10,34	0,81
Bulgaria	15,474	25	NA	8,41	0,62
Hungary	15,250	27	2,2	10,23	0,56
Slovakia	10,381	19	10,7	5,37	0,56
Serbia and Montenegro	9,026	60	NA	10,54	0,15
Croatia	4,644	9	NA	4,78	0,49
Estonia	4,488	4	0,7	1,48	1,03
Lithuania	4,043	8	1	3,72	0,51
Slovenia	3,197	8	NA	1,99	0,41
Moldova	2,952	2	-0,9	4,34	1,54
Macedonia, F,Y,R,	2,934	4	NA	2,16	0,69
Latvia	2,543	6	0,6	2,52	0,46
Bosnia and Hercegovina	503	9	NA	4,38	0,06
Middle Income	427,153	1,372	4,7	323,67	0,31
Korea, Rep,	101,963	288	8,8	44,85	0,35
Brazil	68,012	370	4,5	159,22	0,18
Taiwan	46,720	195	NA	21,3	0,24
Argentina	35,334	149	1,8	34,67	0,24
Malaysia	29,095	71	7,3	20,14	0,41
Trinidad and Tobago	4,670	6	NA	1,29	0,84
Puerto Rico	4,240	36	NA	3,72	0,12
Netherlands Antilles	1,762	,,	NA	..	NA
Cyprus	1,413	7	NA	0,73	0,21
Gabon	967	6	NA	1,1	0,17
Suriname	587	2	NA	0,43	0,36
Martinique	556	,,	NA	..	NA
Malta	471	3	NA	0,37	0,16
New Caledonia	468	,,	NA	..	NA
Reunion	424	,,	NA	..	NA
Macao	336	4	NA	1,97	0,08
Barbados	225	0	NA	1,53	0,75
French Polynesia	153	,,	NA	..	NA
Antigua and Barbuda	88	0	NA	0,07	0,2
Gibraltar	62	,,	NA	..	NA
St, Lucia	52	0	NA	0,16	0,11
Seychelles	44	0	NA	0,08	0,11
Nauru	38	,,	NA	..	NA
St, Kitts	26	0	NA	0,04	0,14
St, Pierre	19	,,	NA	..	NA
Montserrat	12	,,	NA	..	NA
Turks and Caicos	0	,,	NA	..	NA
Isle of Man	,,	,,	NA	..	NA
Northern Mariana Islands	,,	,,	NA	..	NA
Anguilla	,,	,,	NA	..	NA
High-income OPEC	129,416	234	3,7	32,03	0,55
United Arab Emirates	18,642	37	NA	2,46	0,5
Qatar	7,920	7	NA	0,64	1,07
Kuwait	13,297	32	NA	1,55	0,41
Saudi Arabia	69,392	108	3,7	18,98	0,64
Libya	10,754	27	NA	5,41	0,4
Oman	3,116	14	NA	2,14	0,22
Bahrain	4,048	5	NA	0,58	0,77
Brunei	2,247	4	NA	0,29	0,64

Lower-Middle Income	560,578	1,156	3,7	571,42	0,43
Mexico	97,662	179	3,4	91,83	0,54
South Africa	83,462	102	2,1	41,46	0,82
Iran, Islamic Rep,	71,987	211	NA	64,12	0,34
Venezuela	49,193	65	2	21,67	0,76
Turkey	47,773	129	4,3	61,06	0,37
Thailand	47,773	122	7,5	58,24	0,39
Kazakhstan	37,093	18	1,6	16,61	2,04
Algeria	24,909	76	3,4	27,96	0,33
Colombia	18,429	57	4,5	36,81	0,32
Syrian Arab Rep,	12,561	20	6,2	14,11	0,62
Chile	12,037	16	5,2	14,23	0,75
Peru	8,341	28	2,2	23,82	0,3
Morocco	7,995	26	3,9	26,56	0,31
Cuba	7,933	23	NA	11,01	0,35
Turkmenistan	7,733	1	3,6	4,51	5,96
Ecuador	6,177	7	4,5	11,48	0,83
Tunisia	4,178	15	5,1	8,96	0,29
Dominican Rep,	3,212	7	4,5	7,82	0,43
Jamaica	2,470	4	NA	2,52	0,59
Panama	1,882	8	NA	2,63	0,24
Uruguay	1,468	10	1,8	3,18	0,15
Costa	1,428	7	4,1	3,4	0,2
El Salvador	1,416	7	1,9	5,62	0,22
Paraguay	1,036	6	5,2	4,83	0,18
Papua New Guinea	677	5	3,1	4,3	0,13
Guadeloupe	416	,,	NA	..	NA
Mauritius	407	3	NA	1,12	0,13
French Guiana	238	,,	NA	..	NA
Fiji	201	2	NA	0,79	0,11
Belize	113	1	NA	0,22	0,21
Cayman Islands	84	,,	NA	..	NA
American Samoa	75	,,	NA	..	NA
Pacific Islands	65	,,	NA	..	NA
Grenada	46	0	NA	0,1	0,21
St, Vincent and the Grenadines	34	0	NA	0,11	0,15
Tonga	28	0	NA	0,1	0,28
Dominica	22	0	NA	0,07	0,13
Vanuatu	17	0	NA	0,17	0,11
Cook Islands	6	,,	NA	..	NA
Niue	1	,,	NA	..	NA
Namibia	,,	,,	NA	..	NA
Micronesia	,,	,,	NA	..	NA
Marshall Islands	,,	,,	NA	..	NA
Wallis and Futuna	,,	,,	NA	..	NA
China	871,311	654	8,5	1200,24	1,33

Low Income	620,793	1,216	3,4	2377,02	0,51
India	248,017	447	4,4	929,36	0,55
Indonesia	80,822	158	7,1	193,28	0,51
Korea, Dem, Rep,	70,138	15	NA	23,87	4,82
Iraq	27,020	12	NA	20,1	2,33
Uzbekistan	26,986	15	3,3	22,77	1,77
Egypt, Arab Rep,	25,023	48	5,4	57,8	0,53
Pakistan	23,296	56	5,3	129,91	0,42
Philippines	16,692	49	3,4	68,6	0,34
Azerbaijan	11,620	3	-0,2	7,51	3,52
Viet Nam	8,654	68	NA	73,48	0,13
Bangladesh	5,713	27	3,3	57,8	0,21
Yemen	3,933	11	NA	15,27	0,37
Lebanon	3,641	6	NA	4,01	0,57
Jordan	3,632	9	NA	4,21	0,4
Bolivia	2,859	7	2,5	57,8	0,43
Mongolia	2,308	4	NA	2,46	0,55
Georgia	2,114	3	-3,4	5,4	0,8
Guatemala	1,962	11	3,4	10,62	0,18
Myanmar	1,919	15	NA	45,11	0,13
Sri Lanka	1,607	10	4,5	18,11	0,15
Kyrgyzstan	1,491	1	2,4	4,52	1,18
Honduras	1,052	6	3,8	5,92	0,17
Tajikistan	1,021	2	3,4	5,84	0,61
Armenia	996	1	-0,1	3,76	0,83
Nicaragua	737	4	-0,2	4,38	0,18
Albania	504	3	NA	3,26	0,15
Nepal	418	5	3,7	21,46	0,08
Afghanistan	338	14	NA	23,48	0,02
Guyana	255	1	NA	0,83	0,5
Haiti	174	2	0,4	7,17	0,09
Cambodia	136	2	NA	10,02	0,09
Lao, PDR	84	2	NA	4,88	0,04
Bhutan	65	0	NA	0,7	0,14
Western Sahara	57	,,	NA	..	NA
Maldives	50	0	NA	0,25	0,25
Solomon Islands	44	0	NA	0,38	0,16
Western Samoa	36	0	NA	0,17	0,36
Sao Tome and Principe	21	0	NA	0,13	0,29
Kiribati	6	0	NA	0,08	0,17
West Bank	,,	,,	NA	..	NA
Gaza Strip	,,	,,	NA	..	NA
Tuvalu	,,	,,	NA	..	NA
Tokelau	,,	,,	NA	..	NA

Africa	45,352	199	2,7	532	0,23
Swaziland	124	1	NA	0,9	0,13
Lesotho	,,	,,	NA	..	NA
Nigeria	24,759	45	2,9	111,27	0,55
Cote d'Ivoire	2,828	12	2,6	13,98	0,24
Sudan	955	14	NA	26,71	0,07
Kenya	1,824	11	5,2	26,69	0,16
Angola	1,256	8	NA	10,77	0,16
Botswana	612	3	NA	1,46	0,2
Congo	346	3	NA	2,63	0,13
Zaire	573	5	NA	43,85	0,11
Zimbabwe	2,657	8	2,9	11,01	0,35
Ethiopia	962	10	NA	56,4	0,1
Senegal	836	6	2,5	8,47	0,13
Ghana	1,104	8	1,9	17,08	0,14
Zambia	656	3	0,9	8,98	0,25
Madagascar	307	3	0,5	13,65	0,1
Guinea	295	3	NA	6,59	0,1
Cameroon	1,131	11	3,3	13,29	0,1
Uganda	285	12	NA	19,17	0,02
Niger	305	3	0,3	9,03	0,11
Mali	127	3	3	9,79	0,04
Rwanda	134	1	0,8	6,4	0,09
Malawi	198	2	3,7	9,76	0,12
Benin	173	2	NA	5,48	0,08
Somalia	3	1	NA	9,49	0

Appendix ICalibrated elasticity (ε) / Source: own calculation

Year	Japan	USA	OECD Europe	OHI	HIO	MI	Russia	Eastern Europe	LMI	LI	China	India	Africa
1994	1.35000	0.25800	0.25000	0.24000	0.15000	0.21000	0.14500	0.17500	0.17750	0.13500	0.16000	0.15000	0.13300
2004	1.18555	0.26912	0.27522	0.25653	0.15000	0.21000	0.19194	0.21955	0.18623	0.14192	0.19197	0.15928	0.13300
2014	1.07626	0.27928	0.29822	0.27247	0.15000	0.21000	0.23776	0.26059	0.19538	0.14920	0.22317	0.16912	0.13300
2024	1.00149	0.28852	0.31889	0.28774	0.15000	0.21000	0.27997	0.29663	0.20499	0.15685	0.25278	0.17958	0.13300
2034	0.94921	0.29688	0.33726	0.30230	0.15000	0.21000	0.31717	0.32714	0.21507	0.16489	0.28021	0.19069	0.13300
2044	0.91207	0.30442	0.35341	0.31610	0.15000	0.21000	0.34886	0.35226	0.22565	0.17334	0.30512	0.20248	0.13300
2054	0.88536	0.31120	0.36749	0.32914	0.15000	0.21000	0.37517	0.37252	0.23674	0.18223	0.32739	0.21500	0.13300
2064	0.86599	0.31728	0.37968	0.34139	0.15000	0.21000	0.39658	0.38860	0.24838	0.19157	0.34703	0.22829	0.13300
2074	0.85184	0.32271	0.39017	0.35287	0.15000	0.21000	0.41374	0.40122	0.26060	0.20140	0.36416	0.24241	0.13300
2084	0.84145	0.32756	0.39916	0.36359	0.15000	0.21000	0.42734	0.41102	0.27341	0.21172	0.37896	0.25739	0.13300
2094	0.83380	0.33188	0.40682	0.37358	0.15000	0.21000	0.43802	0.41859	0.28685	0.22258	0.39165	0.27331	0.13300
2104	0.82815	0.33572	0.41333	0.38284	0.15000	0.21000	0.44636	0.42440	0.30096	0.23399	0.40247	0.29021	0.13300
2114	0.82397	0.33913	0.41885	0.39143	0.15000	0.21000	0.45282	0.42885	0.31576	0.24599	0.41164	0.30815	0.13300
2124	0.82087	0.34215	0.42352	0.39936	0.15000	0.21000	0.45782	0.43224	0.33128	0.25860	0.41938	0.32720	0.13300
2134	0.81857	0.34482	0.42746	0.40668	0.15000	0.21000	0.46168	0.43482	0.34757	0.27186	0.42589	0.34743	0.13300
2144	0.81687	0.34719	0.43078	0.41341	0.15000	0.21000	0.46464	0.43678	0.36466	0.28579	0.43135	0.36892	0.13300
2154	0.81560	0.34928	0.43357	0.41960	0.15000	0.21000	0.46692	0.43827	0.38259	0.30045	0.43592	0.39172	0.13300
2164	0.81465	0.35112	0.43591	0.42529	0.15000	0.21000	0.46866	0.43940	0.40140	0.31585	0.43973	0.41594	0.13300
2174	0.81395	0.35275	0.43788	0.43049	0.15000	0.21000	0.47000	0.44025	0.42114	0.33205	0.44291	0.44166	0.13300
2184	0.81343	0.35419	0.43953	0.43526	0.15000	0.21000	0.47102	0.44090	0.44185	0.34907	0.44556	0.46896	0.13300