gws Discussion Paper 2010/2 ISSN 1867-7290

Study for the European Environmental Agency, Copenhagen

"Tax reform in Europe over the next decades: implication for the environment, for eco-innovation and for household distribution"

Task A: Eco-innovation

Literature review on eco-innovation and ETR
Modelling of ETR impacts with GINFORS

Ulrike Lehr (GWS)
Christian Lutz (GWS)
Roger Salmons (PSI)

Gesellschaft für Wirtschaftliche Strukturforschung mbH
Heinrichstr. 30
D - 49080 Osnabrück

Ulrike Lehr (lehr@gws-os.com), Christian Lutz (lutz@gws-os.de)
Tel.: +49 (541) 40933-280/-120
Fax: +49 (541) 40933-110
Internet: www.gws-os.de

Policy Studies Institute
50 Hanson Street
London, W1W 6UP
Roger Salmons (salmonr@psi.org.uk)
Tel:+44 20 79 7536
Internet: www.psi.org.uk

Osnabrück, July 2010

CONTENTS

1 ECO-INNOVATIONS AND RENEWABLE ENERGY: INTRODUCTION

Innovation is a strategically important element in domestic and international competitiveness. Due to increasing globalisation, international differences in pricing are becoming more and more apparent, so that quality issues are gaining in importance. Against this backdrop, innovation is regarded as one of the fundamental pre-conditions for survival among the international competition, as well as the crucial engine driving faster growth in the economy as a whole and in the number of well-qualified jobs.

The various fields of policy – not least environmental policy – may promote or restrict innovation. Thus an analysis of the effects on innovation of environmental policy instruments, or combinations of instruments which explicitly influence the behaviour of economic actors, is of especial value, although there is still great uncertainty as to the actual effects themselves.

Moreover, above all in respect of the demand for technology policy to be neutral in its structure and allocating funds, a certain change is becoming apparent in research and environmental policy, which also requires research. Supporting innovation is seen to contain opportunities for better environmental protection and more sustainable, and more support is recommended for so-called environmental innovation or eco-innovation. The focus is above all on innovation which can make a contribution to the environment or sustainability.

The question of how much innovation can contribute to gaining and applying new knowledge for solving urgent economic and social problems is a subject of more discussion now than ever before. Firstly, the growing interest in innovation reflects the concern that some European countries might be falling behind other advancing (industrialised) countries, not only in developing new solutions but also, and above all, in applying them, i.e. in exploiting technological potential for products with a market, in introducing modern management, production and working practices and in opening up global markets. Only with a greater ability to innovate, coupled with competence and a willingness to be creative, it will be possible to give new energy to structural change in the economy, enable faster growth and – above all – to create new jobs.

Secondly, even the most urgent of today's environmental problems cannot be considered solved. In addition to the existing technological options and development paths, innovation which specifically addresses environmental problems will in all probability be required, in order to ensure long-term sustainable development. Alongside a significant improvement in productivity with resources (the efficiency revolution), basic innovation with a long-term yield should be stimulated, opening up more environmentally sound development paths for products and technologies.

However, research is required not only in technology, but also in understanding the necessary framework conditions for bringing about such environmental innovation. As far back as 1996, a study by Zimmermann et al. on the relationship between environmental taxation, innovation and sustainable development determined that "… environmental charges have been grouped together, and their effects over time studied in a variety of ways, but that there are no similar structures for innovation. Two more or less unconnected theories exist alongside one another. For a number of years, there has been a theory of innovation and technological progress within general economic theory, with virtually no reference to the environment. Alongside this, there is some literature on innovation for environmental protection, but with almost no reference to the former complex." (Zimmermann et al., 1996).

This contribution brings together two strands of thought: in section 2 it firstly discusses, coming from the innovation literature, what drives innovation and innovative behaviour in the economy. Secondly it looks extensively at the literature on price instruments, especially environmental tax reform (ETR), and its effects on innovation. From this, we will construct extensions to our scenarios, where some of the ETR revenues are used to foster innovation. The second part from sections 3 to 6 is dedicated to this modelling experience.

The modelling exercise in this second part exceeds the scope of the literature review, because it dwells into the overall effects of a European ETR compared to a baseline development before it actually looks into scenarios designed to explicitly support eco-innovation, or renewable energy sources (RES) technologies as such. Simulations build on the Anglo-German Foundation (AGF) petrE (Resource Productivity and Environmental Tax Reform in Europe) project (Ekins & Speck, 2010). In one of the scenarios 10% of the ETR revenues are earmarked to support investment in renewable energy and energy efficiency to enhance innovation. In further scenarios additional EU exports due to RES investment in other parts of the world and changes in the EU industry structure due to a shift towards RES in the electricity sector are explicitly modelled. With the current enormous increase in RES installation in China and the plans of the Obama administration, these assumptions seem to be more realistic than the quite pessimistic international perspective in the underlying baseline development, which is based on DGTREN (2008) and IEA (2008). The new IEA (2009) WEO will mirror these new perceptions.

2 Eco-innovation in the literature

2.1 Drivers of innovation

To capture the multi-faceted structure of an innovation system one should work from a rather wide definition. Innovation then can mean all artefacts, processes, ideas and strategies that successfully change routines and are implemented in specific contexts of use, which can be changed in turn through the innovation. This definition is wider than some to be found in the literature in the sense that it not only comprises the *invention* of a new process or technology but also its *diffusion*. Therefore, the analysis transcends the analysis of patent data or the introduction of a new technology, but takes the whole innovation system with its intrinsic feed-back loops into consideration. The relations between actors, their co-operation and spill-overs play an important role (see e.g. Carlsson & Stankiewicz 1991, Edquist 2001, Lundvall et al. 2001 and Malerba 2006). The process of innovation is not understood as a linear sequence but rather as a non-linear, highly interactive process as proposed by Kline & Rosenberg (1986) or Rothwell (1995). Hence, we are confronted with a situation where both technology push as well as market pull factors influence the generation and diffusion of innovations (Mowery & Rosenberg 1979, Pavitt 1984).

The importance of innovations for social change, international competition, structural change and economic growth has been analysed quite successfully in the last decade. However, how and why innovation comes about and what triggers it or slows it down is still an open question. There is evidence, that knowledge is the most important input in the process of innovation; the importance of knowledge in certain innovative industries has been empirically shown (Dosi, 1988, Hullmann, 2001). Sparks of innovation emerge through the interplay of different forms of heterogeneous knowledge: their confrontation, combination, fusion, transformation. Different schools of thought describe the accumulation and the distribution of knowledge within the firm, in the economic sector and in innovation system differently.

From an individualistic perspective the analysis focuses on the entrepreneur, who decides about access to knowledge in the firm (Hauschildt, 2004). Evolutionary economics takes a more comprehensive approach and sees the firm as knowledge storage and as part of a wider organizational system (Fagerberg et al., 2005). Additionally, the different knowledge generating processes at the level of the firm like learning by searching, learning by doing or learning by interacting and their respective impact on innovation processes are taken into consideration (Malerba, 1992). With regard to renewable energies there are however just a few studies which analyse the influence of these different learning mechanisms (see e. g. Miketa & Schrattenholzer, 2004) as most analyses are based on the well-known single learning curve approach.

Even though some authors, for instance in the framework of the Innovation Systems Approach (Carlsson & Stankiewicz, 1991, Lundvall et al., 2001, Malerba & Orsenigo, 1997) place a certain emphasis on the importance of both technology push and demand pull factors it has to be stated that up to now ‘demand related aspects still play a minor in the innovation literature’ (Edler et al., 2006). But given the fact that the potential of demand-oriented policy measures is increasingly recognized analyses of customer behaviour gain more and more importance. Especially, the modelling of the various interdependencies between firms’ dynamics, demand dynamics and technology dynamics is considered to be a challenging but crucial task (Malerba, 2005).

Considering the Innovation Systems approach it has moreover been argued that the approach lacked micro-foundations and would not reflect the path dependence of innovation formation due to habit, norms and institutions (see e.g. Rammert, 2002). Rammert argues further that innovation systems currently are undergoing a transition from sequentially organized systems to fractionally structured networks. Though such a system is different for each innovation – a thought that is reflected in the term “biography” of an innovation – Rammert, together with Hage & Hollingsworth (2000) or Amin & Cohendet (2004) assumes that the number of actors from different backgrounds enhance the likelihood of strong innovation activities and their success in the system. However, the more the analysis focuses on the individual biographies, the less the approach becomes suitable for more general recommendations and results.

The lack of knowledge on the drivers of innovations is even more prominent when it comes to studying eco-innovations. The latest OECD publication on eco-innovation

(OECD 2009) states that "Government policy initiatives and programmes that promote eco-innovation are diverse and include both supply-side and demand-side measures." As most countries recognize the need for a more collaborative approach to innovation, many initiatives involve creating networks, platforms or partnerships that engage different industry and non-industry stakeholders. Demand-side measures are receiving increasing attention, as governments acknowledge that insufficiently developed markets are often the key constraint for eco-innovation. (…) A more comprehensive understanding of the interaction between supply and demand for eco-innovation will be a pre-requisite for creating successful eco-innovation policies."

The literature body is larger when it comes to single technologies. Among eco-innovations, much research has been done on technologies for the use of renewable energy sources. Since European energy markets currently undergo significant changes from centralized monopolistic markets to a more competitive environment with a lot of different participants and the challenges from climate change and environmental issues have to be met. Apart from environmental goals, the support policies aim at economic development and technological change. The German feed-in law, for instance, has already triggered the rapid development in the German wind industry and in the photovoltaic industry. But it is widely agreed that still a lot of innovation is needed for technologies to provide clean electricity at affordable cost at a large scale for the future.

Success factors in these innovation systems hinge on a wide array of determinants. They differ depending on the innovation phase, the technology and the actors, institutions and participants in the innovation system. For instance, the technological system for solar cells exhibits some very interesting characteristics (Roloff et al., 2008): Firstly, the technology as such has been known for more than 100 years by now (Green, 2000). However, the technological development was dominated by 'science-based experimentation' until the 1990s. Solar cells were first used for extraterrestrial applications during the so called 'Space Age' (1958 to 1973). Later on they were also used for consumer electronic products as well as for off-grid power systems (1974 until mid-1990s). Nevertheless public policy measures still had a strong focus on the support of R&D activities. Until Japan and Germany started their first demand-oriented programs during the 1990s the role of photovoltaics with regard to the supply of energy thus remained quite limited. These initiatives and successive programmes and regulative changes eventually led towards a significant growth of the PV-industry and therefore to an expansion of the whole technological system (Jacobsson et al., 2002). As the technology evolved, the motifs of actors changed and new actors have been attracted to the field.

Other case studies show similar effects, for instance on wind energy supported by tax breaks in Texas (Langniss, 2003), introduction of wind energy in Denmark supported by R&D support and demand oriented instruments as the most important instrument, or the German example with successful diffusion of innovative production technologies due to demand support mechanisms and low interest rates on credits for wind mills.

The Japanese and the German experience with solar modules seem to support the hypothesis that R&D support, followed by demand side mechanisms and a strong regulatory framework promote innovations. The guaranteed market created by demand side instruments helps diffusion of innovative products *and* the invention by innovative firms as well. R&D support and tax breaks, however, have proved to be successful as well, as long as the system is transparent and continuous.

However, these studies focused on success or failure case studies of specific eco-innovations such as wind mills or solar panels. To get a complete picture, we carried out a literature view on the reversed question: given a certain instrument, what type and phase of eco-innovations benefits or looses? Since our study focuses on an Environmental Tax Reform, the more important answers will come from the body of literature on ETR and eco-innovation.

One cautionary remark in advance: Though innovation is seemingly triggered by the mere existence of ETR, i.e. by the respective price changes, the innovative efforts will be distributed over all energy applications. Specific funds allocation seems to be necessary if the innovative potential has to be guided towards certain applications such as renewable energy technologies of certain efficiency technologies.

2.2 Environmental tax reform and eco-innovation [1]

2.2.1 Introduction

A two-step methodology has been employed for the literature review. In the first step, potential references were identified and screened in order to determine their relevance to the topic and to classify them along four relevant dimensions. In the second step, those references that were identified as being of significant relevance were reviewed in detail in order to distill the key conclusions regarding the potential implications of environmental tax reform for eco-innovation.

There is a relatively large (and growing) literature on the relationship between environmental policy interventions and technological innovation – both theoretical and empirical. While this covers a wide range of policy instruments (i.e. command and control regulations, environmental taxes, permit trading schemes and voluntary agreements), only one of the identified references considers explicitly the impacts of an environmental tax reform (ETR) programme. Consequently, this review has focused on those studies that have assessed the impacts of environmental taxes (and in some cases, factor prices) on innovation. However, in order to provide some context, the impacts of environmental regulation more generally are also considered.

Before proceeding, it is worth clarifying what is meant by innovation (in general) and by eco-innovation (in particular). Following *Schumpeter* (1942), the process of technological change is typically broken down into the following three stages:[2]

---

1 This section has been prepared by **Roger Salmons, Policy Studies Institute**

2 Some authors break down the innovation stage into two: the application of inventions in demonstration projects; the development of niche applications and markets (e.g. *Christiansen & Skjaerseth*, 2005).

- invention – i.e. the first development of a scientifically or technically new product or process;
- innovation – i.e. the commercialization of the new product or process;
- diffusion – i.e. the adoption of the product or process by firms and individuals.

The first two stages are closely related, although not all inventions will make it through to commercialization. They typically both occur in private companies in a process that can be broadly termed research and development (R&D).

When considering the impacts of environmental policy interventions it is important to be clear which stage of the technological development process one is considering as different instruments may be more, or less, effective for different stages. Many of the studies explicitly identify the technological development stage to which they relate. For those that do not, it is sometimes possible to infer the stage from the context and / or characteristics of the study (e.g. the measure of innovation that is used). However, some studies refer only to "investment in technology" and it is not clear whether this means investing in the development of new products and / or production processes (i.e. invention and innovation) or purchasing new plant and equipment from other companies (i.e. diffusion).

The term "eco-innovation" is taken to mean technological development that generates products, equipment or production processes that reduce environmental risk or minimize pollution and resource use. As such, the term encompasses all three stages of the technological development process – i.e. invention, innovation and diffusion.

There are a range of different indicators that can be used to measure innovation. Essentially these indicators fall into three groups: those that measure the inputs (or resources) devoted to the innovation process; those that measure the outputs from the process; and those that focus on the economic impacts of the innovations that are generated (Johnstone et al., 2008).

The most common input indicator is R&D expenditure. However, there are a number of problems with this. While public sector R&D expenditure data is generally available, private sector expenditure data is incomplete and usually only available at the aggregate level, making it difficult (or impossible) to identify environmentally-related R&D expenditure. Furthermore, given the inherent uncertainty of the innovation process, the link between effort and resultant outputs is often very weak. Consequently, output indicators such as patent applications are likely to provide a better vehicle for measuring eco-innovation. Patent application data provides a reasonably comprehensive picture of innovative outputs[3]; is based on objective standards that change slowly; and is readily available. The main advantage however is the fact that patent applications are classified into detailed technologies (using the International Patent Classification (IPC) system developed by the World Intellectual Property Organisation). This allows the identification

[3] While a patent may prevent rival firms from utilizing an innovation (without paying royalties), it has the disadvantage of putting it into the public domain. In some cases, firms may prefer to keep the innovation secret rather than apply for patent protection.

of environmentally-related patents; broken down between different application areas – e.g. climate change, air pollution, water pollutions, waste management, etc. Impact indicators (also termed progress indicators) are more relevant to the diffusion stage and include increases in market penetration of particular eco-technologies and reductions in (marginal) abatement costs.[4] However, it should be noted that cost reductions can be driven by a range of factors and may not necessarily imply that that innovation has occurred.

2.2.2 Initial screening

Potential references were identified based on a review of journal citations, internet searches using keywords and recommendations from within the project team. The references fall into three broad groups:

- refereed journal articles;
- books and book chapters;
- reports by consultants and experts

In total, thirty-seven potential references were identified; the majority (twenty-eight) being refereed journal articles. The references were then classified along four dimensions: type of study; policy instrument(s) covered; policy area; technological development stage. On the basis of this classification, each reference was then assessed in terms of its relevance.

A distinction is made between five different types of study. *Theoretical studies* use mathematical models to assess the impacts of "idealized" policy instruments on firms' innovative behaviour under alternative assumptions about market structure and different parameter values. In most cases, the studies consider several alternative instruments and are interested in the relative ranking of the instruments, either in terms of the amount of innovation that they induce, or in terms impacts of the resultant levels of social welfare. *Empirical studies* use a range of statistical and econometric techniques to analyse quantitative performance data in order to assess the impacts of "actual" policy interventions. Given the relative scarcity of environmental taxes in the past, there are few explicit studies of this instrument. However, a number of studies consider the impacts of changes in energy prices, which give an indirect indication of the potential impact of taxation. *Reviews* summarize and / or compare the findings of previous studies (either theoretical or empirical) and may synthesize these to draw wider conclusions. *Case studies* provide descriptive assessments of actual experiences, often comparing across countries; while q*ualitative studies* consider some of the issues that can affect the performance of a particular policy instrument in practice. Together, these last two types of study can provide valuable insights on the practical and "political economy" aspects of instrument performance, to supplement the theoretical and empirical analyses.

[4] More correctly, shifts in the abatement cost curves should be used – i.e. a reduction in cost for a fixed level of abatement. Reductions due to movements along the cost curve (i.e. due to changes in the level of abatement) do not provide an indicator of innovation.

The second classification dimension concerns the policy instruments that are addressed by the study, with a distinction being made between five specific instrument types. The first three are market-based, or price-based, instruments: *environmental taxes and charges*, *tradable permits* and *investment subsidies and tax allowances*; all of which act by changing the prices of input factors in one way or another. As has been noted above, some studies consider the impact of energy prices rather than energy taxes *per se*. However, since the findings of these studies are directly transferable, they are classified under the tax heading. The fourth instrument type is *voluntary / negotiated agreements*, under which firms or sectors enter into agreements with government to achieve certain performance targets or undertake specific actions. The fifth type is *command and control regulations*, which encompasses technology mandates, emission limits and performance standards (e.g. for specific energy consumption). The final classification – *regulation* – is used for studies that consider the weight or stringency of environmental regulation in general, rather than any specific policy instrument.

With regard to the policy area(s) covered by the studies, a distinction is made between *energy and climate change*, *air pollution*, *water pollution* and *other* policy areas. Again, there is a final classification – *general* – which is used for studies that consider the impacts of environmental regulation in general rather than any specific intervention, or where the policy area is not specified (e.g. in theoretical analyses).

The final classification dimension concerns the stage of the technological development process that is addressed by the study. As has been noted above, the process is typically divided in to three stages: invention, innovation and diffusion. However, in practice the studies do not distinguish between the first two stages (often just referring generically to R&D) and hence they have been combined for the purposes of the classification, so that the only distinction is between the *innovation* and *diffusion* stages.

Based on the results of the classification exercise, each of the studies is scored in terms of its relevance to the object of the review – i.e. the impact of ETR on eco-innovation. A three tier qualitative scoring system is used; with one star (*) indicating that the study is of only minor relevance, two stars (**) indicating that it is of moderate relevance, and three stars (***) that it is of significant relevance. Such a scoring system is inevitably subjective, but it provides a pragmatic mechanism for identifying the key references to be included in the detailed review. In determining the scores, particular emphasis was placed on whether the study is empirical in nature and whether it considers environmental taxes (or factor prices).

Annex 1 shows the classifications of the twenty-eight journal articles that were identified. Thirteen are empirical, seven are theoretical, three are case studies and four are qualitative, while four provide reviews of previous work in the area (including most of the identified studies).[5] Around two-thirds of the papers consider the impact of environmental taxes (or energy prices), often comparing these with the impacts of other policy instruments; while eleven consider the impact of investment subsidies. While most of the

[5] Some studies are classified under more than one heading. For example, a study may contain both a theoretical model of behaviour and an empirical assessment of the model.

theoretical analyses are not area-specific (talking only about environmental damage in general terms); the empirical studies are spread fairly evenly across policy areas, with five each in energy / climate change and air pollution and three in water pollution. In terms of stage of the technological development process, there is an even split between innovation and diffusion, with many of the papers covering both stages. In total, eighteen of the references are included in the detailed review.

Annexes 2 and 3 show respectively the classifications of the five book chapters and four reports.[6] As one might expect, there is less emphasis on theory, with only one reference including any formal analysis. The other references are split fairly evenly between empirical studies, reviews and qualitative assessments. All but one consider the impact of environmental taxes or energy prices, while seven consider the impact of investment subsidies. As with the journal articles, there is a fairly even spread across policy areas and between innovation and diffusion. Five of the references are included in the detailed review.

2.2.3 Detailed review

The detailed review focuses on the impacts on eco-innovation of the two "price-based" policy instruments that are directly relevant to ETR: environmental taxes; investment subsidies and tax incentives (e.g. R&D and capital allowances).[7] *A priori*, each instrument might be expected to stimulate innovation; the first by increasing the benefits of innovation (i.e. by reducing tax payments); the second by reducing the costs of developing and / or adopting new technologies. However, in order to provide a broader context for the impacts of these two instruments, the review starts by considering the relationship between the stringency of environmental regulation in general and innovation.

As can be seen from the initial screening (see Annexes 1-3), the large majority of studies consider more than one policy instrument within a unified analytical framework – either comparing their relative impacts, or assessing the impacts of instrument combinations (or packages). In particular, all but one of the papers that assess the impacts of investment subsidies, either theoretically or empirically, also assess the impacts environmental taxes (and sometimes other policy instruments). Consequently, for the purposes of this review, it is convenient to consider the impacts of taxes and subsidies at the same time, rather than sequentially. In addition to avoiding the need for any repetition (about model structures, assumptions, etc.), this facilitates the identification of potential interactions and synergies between the two instruments.

---

6 Two of the reports emanate from the study by Ecologic and DIW of the ETR in Germany. Details of the assessment of the impact on innovation and market diffusion are provided (in German) in *Görlach et al.* (2005); with a summary being provided (in English) in *Knigge & Görlach* (2005).

7 While the (large) majority of revenues raised under an ETR are likely to be used to reduce taxes on labour, a small proportion may be used to encourage innovation and / or promote the take-up of environmentally-friendly technologies.

Apart from the initial sub-section on the impact of environmental regulation in general, only those references identified as being of significant relevance (***) in the initial screening are included in the review. References are summarised in chronological order under three headings: theoretical predictions (section 2.2.5); empirical evidence (section 2.2.6); and case studies (section 2.2.7). At the end of each section, an attempt is made to synthesize the findings of the references. However, due to the tight budgetary constraints for the review, it has not been possible to undertake any critical analyses of the studies to identify their respective strengths and weaknesses, or to resolve any apparent conflicts between their respective findings.

2.2.4 Environmental regulation

Lanjouw & Mody (1996) use aggregate pollution and control expenditure (PACE) data as a proxy for the stringency of environmental regulation and compare this with data on the aggregate number of environmental patent applications for Germany, Japan and the USA. They do not perform any formal statistical / econometric analysis of the data. However, based on simple graphical analysis, they identify a relatively clear correlation between expenditure and patents over the 1970s and 1980s, with a time lag of 1-2 years. They also find some indications in the data that patenting in a country also responds to increasing stringency of environmental regulation in the other two. In addition, they consider the diffusion of environmental technologies by looking at trade flows in capital goods used for pollution reduction; finding that these too show a correlation with total abatement expenditure.

Jaffe & Palmer (1997) also use PACE data as a proxy for the stringency of environmental regulation and evaluate the impact of this on two different measures of innovation – total private expenditures on R&D and the number of successful patent applications by US manufacturing industries. Unlike the previous study, they undertake formal econometric analysis of the data, using panel data at the two-digit and three-digit SIC code industry level for the period 1978-1991 and a fixed effects model. They find a statistically significant positive relationship between compliance expenditures (capital expenditures only) and R&D expenditures after controlling for industry-specific effects.[8] However, they can find no significant impact on patenting activity. This is not entirely surprising given the fact that their data is for all types of patents, not just those relating to environmental technologies and products. Indeed, given that the same is true for the R&D expenditure data, it may be more surprising that they find a significant relationship between pollution compliance and R&D.

Brunnermeier & Cohen (2003) also use a panel data model to assess the impact of pollution abatement expenditures on patenting activity by US manufacturing industries. However, unlike the previous study, they use only environmental patent applications in

[8] When they allow the slopes of the PACE variable to vary across industries (in addition to the intercept), they find considerable variation in the estimated coefficients across industries – with a number being negative.

their analysis. They also control for other potential explanatory factors, such as the stringency of monitoring and enforcement (as measured by number of inspection visits); industry size (value of shipments); market structure (four-firm concentration ratio); capital intensity; and exposure to overseas competition (export intensity). They estimate four different models for the period 1983-92; with their preferred model being a negative binomial random effects model. The coefficient for PACE is positive and statistically significant (in all four models), as are the coefficients (in the preferred model) for industry size, concentration and export intensity. However, the magnitude of the coefficient (which represents the semi-elasticity of patents with respect to PACE) is only 0.0004. Thus, *ceteris paribus*, an increase in abatement expenditure of $100 million results in an increase in the mean number of patents of only 4%.

All three studies use PACE data as a proxy for the stringency of environmental regulation.[9] While there are obvious pragmatic reasons for doing this (i.e. availability of data), the validity of the approach may be open to question. As *Brunnermeier & Cohen* (2003) note, expenditure may be affected by factors other than environmental regulation, such as external pressures from interest groups, or a desire to promote / maintain "green credentials" with customers. Furthermore, the reported data may not cover all pollution abatement costs and activities (particularly process related activities) and may be prone to over-statement by reporting firms for strategic reasons. However, to the extent that the reported PACE data is correlated with the stringency of environmental regulation, the analyses suggest that the latter does have an impact on innovation (at least in the USA), although the scale of the impact appears to be small.

2.2.5 THEORETICAL PREDICTIONS

Although there had been a number of previous analyses of the impact of different environmental policy instruments on technological change, *Milliman & Prince* (1989) were the first to consider the entire process of technological change, encompassing innovation, diffusion and optimal agency response.[10] Using a relatively simple graphical analysis of shifting marginal abatement cost curves, they deduce a relative ranking of five instruments (direct controls, auctioned permits, freely allocated permits, emission reduction subsidies[11] and emission taxes) in terms of firms' incentives to promote technological change. They conclude that emission taxes provide greater incentives for innovation and diffusion than direct controls or freely allocated tradable permits, although

---

9 However, the studies do not all use the same definition of PACE. *Lanjouw & Mody* (1996) include (real) investment expenditures, regulation and monitoring costs, and research and development by all levels of government, and by private manufacturing and non-manufacturing firms. The other two studies both use compliance cost data for private manufacturing firms (at the industry level) only. However, while *Jaffe & Palmer* (1997) use capital cost data in their analysis, *Brunnermeier & Cohen* (2003) use operating cost data.

10 *Milliman & Prince* (1989) identify a number of studies going back to 1970.

11 These are payments for emission reductions – not technology subsidies for environmental investments.

not as great as auctioned permits. However, optimal agency response is likely to face less opposition (and in some cases actually be favoured) under emission taxes than under auctioned permits.[12]

Jaffe & Stavins (1995) develop a theoretical framework for comparing empirically the impacts of alternative policy instruments on the diffusion of a new technology.[13] They model the investment decision for both an existing firm and a new entrant; in each case assuming that the firm minimizes the present value of its cost streams over time – comprising operating costs, investment cost (net of any government subsidy), emission taxes and the implicit costs of violating either a performance or technology standard (if applicable). For an existing firm, the problem is to choose the optimal timing of the retrofit and the authors show that the new technology will be adopted at a particular time if operating cost savings plus savings from reduced emission tax payments (plus any avoided penalties for not adopting a technology standard or exceeding a performance standard) in that period are greater than the net investment costs less the time rate of change of net investment costs. For a new entrant, the problem is to choose whether to use the new technology at start-up. A necessary condition for doing so is that the present value of operating costs savings and reduced tax payments (plus any avoided penalties) over the entire time horizon is greater than the net investment cost. Thus, while the conditions differ, in each case the introduction of either an emissions tax or an investment subsidy (or increases in the respective values) changes the benefit-cost balance in favour of the new technology; bringing forward its adoption by existing firms and increasing the likelihood of adoption by new entrants.

Kemp (1997) compares the abatement R&D expenditure levels of an individual firm under direct regulation (i.e. an emissions limit), an equivalent emission tax[14], freely-allocated tradable permits, using a cost minimization analytical framework and a specific functional form for the abatement cost function. He shows that both the level of R&D expenditure and the level of emissions reduction increase as the emissions tax rate increases and that both are greater under the tax than under direct regulation. The corresponding levels under the tradable permit regime will be greater / lesser than under the emissions tax depending on whether the (exogenous) permit price is higher / lower than the tax rate. He also considers the impact of subsidizing the cost of the firm's R&D effort and shows that increasing the subsidy rate causes a rise in pollution-control R&D. More interestingly, the impact of the subsidy is greater if it is combined with an emissions tax than with an equivalent emissions limit.

Fischer et al. (2003) develop the approach used by (Milliman & Prince (MP), 1989), although their analysis differs in that it does not include the final agency response stage

[12] For an emissions tax, the downward shift of the industry marginal abatement cost curve as a result of diffusion causes the agency to reduce the tax rate, assuming that marginal damages are increasing in emissions. For permits (auctioned or freely allocated) it causes the agency to reduce the number of permits.

[13] The empirical application of this framework is summarised below under empirical evidence.

[14] That is, the emissions tax is set equal to the firm's marginal cost of abatement under the direct regulation.

and the diffusion of the technology is determined by market forces with an equilibrium royalty price.[15] They compare an emissions tax with auctioned and freely-allocated permits using a three-stage model of innovation, diffusion and emissions abatement. In the first stage, the innovating firm decides how much to invest in R&D to develop an emissions abatement technology. In the second stage, other firms decide whether to adopt this technology in return for a royalty fee, or whether to use an (imperfect) imitation technology. In the final stage, all firms choose their level of abatement to minimize costs given an emissions-tax or permit price. They show that the level of innovation (i.e. the level of R&D chosen by the innovating firm) is determined by equating the marginal cost of innovation with the marginal (private) benefit; where the latter has four components: an *abatement cost effect*; an *emissions payment effect*; an *imitation effect*; an *adoption price affect*; where the last two components are negative[16] Using this model, the authors demonstrate that freely-allocated permits provide the lowest incentive for innovation. However, in contrast to MP, they conclude that the relative ranking of the emissions-tax and auctioned permits is ambiguous – depending crucially on the extent to which the technology can be imitated and hence, the extent to which the innovator can appropriate the gains accruing to the other firms in the form of royalty payments. If imitation is high (easy), then auctioned permits provide the greater incentive for innovation. However, if imitation is low (difficult), then the emissions-tax provides the greatest incentive.

Montero (2002) assesses the impacts of alternative policy instruments on environmental innovation (as measured by R&D expenditure) under conditions of imperfect competition. In his model, two firms compete in either quantities (i.e. Cournot duopoly) or prices (i.e. Bertrand duopoly), while being subject to some form of environmental regulation. Where the regulation takes the form of tradable permits – either auctioned or freely-allocated – the market is also assumed to be imperfect, the firms competing in permit quantities. The interaction between the two firms is modeled as a multi-stage game, with the number of stages depending on the instrument being analysed. In this framework, a firm's incentive to invest in R&D comprises two components: a direct or *cost minimizing effect* and a *strategic effect*, reflecting the impact of its R&D expenditure on the other firm's output decision. The latter may be positive or negative depending on the market-regulatory structure. Under Bertrand competition (i.e. where products are strategic complements), freely-allocated permits provide the lowest incentive for innovation, followed by the emission-standard; while the relative ranking of an emissions-tax and auctioned permits is ambiguous, depending on model parameter values. Under Cournot competition (i.e. where products are strategic substitutes), the relative ranking of the emissions-tax, auctioned permits and the emissions-standard are ambiguous, although all provide a greater incentive than freely-allocated permits. Indeed, the author provides a numerical example where the emissions-standard provides the greatest incentive for innovation. Finally, he considers the

---

15 In addition to assessing the impacts on the demand for innovation, *Fischer et al* (2003) consider the impacts of the innovation / diffusion process on social welfare in order to compare the overall economic efficiency of the different instruments.

16 MP capture only the first two effects in their analysis.

impact of increasing competition (by increasing the number of firms) and concludes that under perfect competition, the emissions-tax provides the greatest incentive for innovation.

Millock & Nauges (2006) use a simple profit optimization model to analyse a firm's choice of abatement effort to reduce emissions per unit of energy used in production. While they do not explicitly identify it as such, this effort can be interpreted in terms of diffusion of an existing technology – with higher effort corresponding to greater diffusion. This is consistent with the overall objective of their study, which is to assess the impact of combining an emissions-tax with a subsidy on (existing) abatement equipment.[17] In their model, the firm simultaneously chooses the levels of its energy input and abatement effort, given exogenous output and energy prices, and a cost function for abatement effort.[18] They show that while increases in the subsidy rate (expressed as a percentage of the gross investment cost) unambiguously increases abatement effort, the impact of increases in the tax rate depends on whether the direct impact of tax increase on the marginal benefit of abatement effort (i.e. shifting it up) outweighs the indirect impact via the resultant reduction in output (i.e. shifting it down). If the latter dominates, then increases in the tax rate will reduce the optimal level of abatement effort. The authors show that a necessary and sufficient condition for the direct impact to dominate is that the slope of the firm's (inverse) demand for energy is greater than the average emissions-tax payment per unit of energy in relation to total energy use.[19]

McGinty & de Vries (2009) analyse the relationship between environmental subsidies, the diffusion of a clean technology, and the degree of product differentiation in an imperfectly competitive output market. In their model, a fixed number of firms can choose individually between using a "clean" production technology and a "dirty" technology. Both technologies exhibit constant marginal production costs and constant emission rates (with the clean technology having a lower emission rate and higher unit cost) and consumers are assumed to be able to differentiate between products on the basis of the technology used in their production.[20] The subsidy regime is different to that considered by the other studies, in that it is applied to the production cost of the clean good – i.e. it reduces the (constant) marginal cost of production for that good. As such, it is equivalent to an output subsidy for the clean good. The authors derive the equilibrium diffusion rate for the clean technology (i.e. the proportion of firms using that technology) and show that an increase in the subsidy

---

[17] In the second half of their paper, *Millock & Nauges* (2006) undertake an empirical evaluation of such a scheme that operated in France during the 1990s for SO_2 and NO_X emissions. The results of this analysis are summarised under empirical evidence.

[18] Abatement effort is assumed to exhibit decreasing returns to scale – i.e. the cost function is increasing and convex.

[19] If output is held fixed in the profit maximization problem, then increases in the emissions tax rate unambiguously increase the optimal level of abatement effort, as was found by *Kemp* (1997) who uses a cost minimization framework for his analysis.

[20] The model assumes imperfect substitution between the "clean good" and "dirty good", with the willingness-to-pay for one good being a linear function of the quantities of both goods individually – i.e. $P_k = a_k – bY_k – cY_j$.

value increases diffusion for all degrees of product differentiation; with the impact being greater, the closer the substitutability of the two goods. They also briefly consider the impact of a technology subsidy that reduces the fixed cost of the clean technology and conclude that this too will stimulate diffusion, but that it will be less efficient than the output subsidy.[21]

As is often the case with theoretical analyses, the specifications of the models and the underlying assumptions can have a significant bearing on the conclusions. Notwithstanding this, there is a reasonable degree of consistency between the findings of the studies considered here. The studies can be classified into two broad groups: those that consider innovation and diffusion within an industry setting; and those that consider an individual firm's decision whether to invest in an abatement technology (i.e. diffusion) or undertake R&D (i.e. innovation) in order to reduce its own cost of abatement.

The studies in the first group conclude that under conditions of perfect competition, emission taxes and auctioned permits provide greater incentives for innovation than direct controls or freely allocated permits. However, there is some disagreement over the relative impacts of the two instruments. Under the assumption that the innovator appropriates a fixed (exogenous) proportion of the gains accruing to the technology adopters, *Milliman & Prince* (1989) conclude that auctioned permits provide the greatest incentive, although the government may find it easier to adjust emission taxes in response to the resultant downward shift in marginal abatement costs. However, when the proportion is determined endogenously – in the form of a royalty payment – *Fischer et al.* (2003) find that either auctioned permits or emission taxes can provide the greater incentive. Emission taxes are likely to provide the greatest incentive if the innovator can appropriate a large proportion of the gains (because the technology is difficult to imitate). *Montero* (2002) uses a slightly different framework to compare the impacts of different instruments on innovation (in the form of R&D expenditure) in a situation of imperfect competition and finds that the ranking depends on the nature of the competition.[22] Under Bertrand price competition in the output market the results are the same as under perfect competition: the relative ranking of auctioned permits and taxes is ambiguous, but both provide greater incentives for innovation than emission standards and freely allocated permits. However, under Cournot quantity competition, any of the instruments apart from freely allocated permits can provide the greatest incentives, depending on the model parameter values.

The studies looking at an individual firm's decision also show that an emissions tax can stimulate innovation and diffusion. *Jaffe & Stavins* (1995) consider explicitly the firm's decision criterion for investing in a new abatement technology and show that, by increasing the benefits of investing, the introduction of an emissions tax should bring

---

[21] M*cGinty & de Vries* (2009) derive expressions for the necessary technology subsidy values when diffusion is 0% and when it is 100%. They state – without proof – that the latter is greater than the former. Provided that the relationship between the subsidy and diffusion is monotonic, this is a sufficient condition for increases in the subsidy value to cause increases in diffusion.

[22] Montero's model does not include diffusion. However, it does include spillover effects, where R&D by one firm reduces the abatement costs of the others.

forward the timing of its adoption by existing firms and make it more likely to be used by new entrants. The other two studies consider the firm's choice of optimal "abatement effort" in the context of maximizing its total profits or minimizing its total cost of emissions reduction. This effort can take the form of R&D (innovation) or expenditure on abatement equipment (diffusion); the decision problem being the same in each case – i.e. to choose the optimal level of effort. *Kemp* (1997) assumes that the firm seeks to minimize its total cost of emissions reduction – implicitly assuming that its output level is fixed – and demonstrates both that abatement effort increases as the emissions tax increases and that the optimal effort is lower under direct regulation than under an equivalent tax. However, when the firm's output level is allowed to vary – as is the case with the profit maximization problem considered by *Millock & Nauges* (2006) – the impact of an increase in the emissions tax rate on the level of abatement effort depends on the relative magnitudes of the direct impact and the indirect impact (via changes in output levels) on the marginal benefit of abatement effort. If the latter dominates, then an increase in the emissions tax rate leads to a reduction in the optimal level of abatement effort.

Only one of the industry-models considers the impact of investment subsidies. Using a product differentiation model of imperfect competition, *McGinty & de Vries* (2009) show that subsidizing the unit cost of a clean production technology can accelerate its diffusion. However, the impact depends on the degree of substitutability between clean and dirty products; diminishing as the products become more differentiated. In contrast, all three of the individual firm analyses consider the impact of investment subsidies, with all demonstrating that increasing subsidies induce greater abatement effort. Furthermore, *Kemp* (1997) shows that the impact of an R&D subsidy is greater in the presence of an emissions tax than it is under an equivalent emissions-limit.

2.2.6 Empirical evidence

Jaffe & Stavins (1995) use their theoretical framework[23] as the basis for assessing the diffusion of thermal insulation in new home construction in the United States, using state-level panel data for the years 1979-88. They derive a reduced form equation for the energy efficiency level chosen by developers from the marginal cost / benefit condition; in which the explanatory variables include energy prices, installation costs and the presence of a relevant building code (as a dummy variable). Separate equations are estimated for ceiling, floor and wall insulation, with the coefficient for energy prices being positive in all three equations. Although it is only significant (at the 95% level) for floor insulation, the joint hypothesis that all price coefficients are zero is strongly rejected. However, the coefficients for installation cost (which are all negative as expected) are around 2-3 times greater in magnitude and of comparable significance. The coefficients for the building code dummies are consistently insignificant (and negative in two cases), indicating that this form of direct regulation had minimal impact on household energy efficiency levels over the period. The authors use the estimated models in a simulation to compare the effects of a 10% increase

[23] See above.

in energy prices (i.e. an energy tax) with those of a 10% reduction in installation costs (i.e. a technology subsidy) – with each being applied over the whole ten-year period. While the tax increases diffusion by between 2%-6% by the end of the period, the technology subsidy increases diffusion by between 4%-15%.

Kemp (1997) models the diffusion of biological water treatment technology in the Dutch food and beverage industry based on a rational choice threshold model of technology adoption decisions. In this model, a firm chooses to adopt an abatement technology if the resultant reduction in emission-tax payments is greater than the annualized total costs of the technology, where a discount factor is applied to the savings to reflect uncertainty and risk aversion on the part of the decision-maker. This is translated into a probabilistic model under the assumption that both the savings and the costs follow a lognormal distribution across plants. The model is estimated econometrically using data for the period 1974-91 under different assumptions for the functional form of the discount factor and allowing for adjustment costs.[24] The estimated parameters for the preferred specification of the discount factor are all significant and of the expected sign and magnitude, and the model provides a very close fit to the actual diffusion of waste-water treatment technologies over the period. This leads the author to conclude that the effluent charges were a significant positive factor in the diffusion of treatment technologies. Indeed, he estimates that only around 4% of plants would have installed waste-water treatment equipment by the end of the period if the charge had remained at its (low) 1974 level, compared to the actual figure of over 40%.

Newell et al. (1999) estimate the impact of energy prices, energy efficiency standards and other factors on the energy efficiency of three types of electrical consumer durables (room air conditioners, central air conditioners and gas water heaters) in the USA between the 1970s and 1990s. The analysis utilizes a product characteristics model in which the frontier of technologically feasible products is described by a "transformation surface" that relates the bundle of product characteristics to real cost of producing that bundle. In this framework, innovation is represented by movements of the surface and / or movements along the surface. In particular, the authors identify three types of innovation: shifts in the surface towards the origin (*overall technological change*); changes in the slope of the surface (*directional technological change*); changes in the mix of products along a given surface (*model substitution*). They define the surface in terms of two characteristics, energy flow and cooling capacity, and incorporate innovation by allowing the coefficients of the two variables to vary with time and (in the case of energy flow) energy prices and efficiency standards. Separate equations are estimated for each durable type with (slightly) differing sets of explanatory variables and time periods. They find little evidence that either energy prices or energy efficiency standards had any impact on overall technological change. While all but one of the relevant coefficients have the expected sign, none are significant. In contrast, they do find evidence that energy prices had an impact on

---

24 Adjustment costs are accounted for by estimating a partial adjustment model in which the actual change in adoption is some fixed fraction of the desired change (estimated from the threshold model).

directional technological change, with the relevant coefficients being of the correct sign and significant for both room and central air conditioners.

Popp (2002) uses patent data to estimate the effect of energy prices on energy-efficiency innovations in the USA between 1970 and 1994. He regresses normalized energy efficiency related patent applications against energy prices, controlling also for lagged knowledge stock and government R&D.[25] The estimated coefficient for energy prices is highly significant; giving a short-run price elasticity of 0.06 and a long-run elasticity 0.354. Thus, a 10% increase in energy prices would be expected to increase the number of energy efficiency related patents by around 3.5% in the long run. The estimated mean lag is less than 4 years, leading the author to conclude that the imposition of a carbon / energy tax would lead to a fairly quick shift towards environmentally friendly innovation.

Hoglund Isaksson (2005) estimates abatement cost functions for the reduction of NO_X emissions in three industrial sectors in Sweden (energy, pulp and paper, chemicals and food). The analysis uses a double-hurdle model applied to a pooled sample of 114 plants across the three sectors. The data covers the period 1990-96, which spans the introduction of the charge on NO_X emissions in 1992. The estimated cost curves have a similar shape in all three sectors, with minimal (or even negative) costs over a relatively broad range of emission reductions and then a steep rise as reductions exceed a threshold level. The analysis does not explicitly consider the issue of innovation. However, it does find that abatement cost curves shifted downwards significantly over the period. In the energy sector for example, the emission rate threshold for significant cost increases fell by around 45% between 1991 and 1996 (from 550 to 300 kg/GWh). The author surmises that this is due to a combination of technological development and the discovery of previously unrecognized opportunities. Unfortunately, while this shift coincided with the introduction of the NO_X charge, the analysis does not provide any evidence of a causal link.

As part of their analysis of the impacts of the French tax-subsidy scheme for NO_X and SO_2 emissions, *Millock & Nauges* (2006) estimate the impact of the emission taxes on a plant's decision to install end-of pipe abatement equipment. While the study is not concerned with innovation *per se*, the results of this part can be interpreted as showing the impact of emission taxes on the diffusion of abatement equipment. Under the scheme, taxes were imposed on the emissions of these air pollutants (and VOCs) by all plants satisfying certain criteria. The revenue raised by the taxes was earmarked for subsidizing the cost of qualifying abatement technologies, for technical studies (i.e. R&D) and for investment in air quality surveillance systems. Using panel data for 226 plants in three industries (iron and steel, coke and chemicals) for the period 1900-98, the authors estimate a Probit model for the probability that a plant will install abatement equipment. They find that the total value of emissions taxes paid by the plant (i.e. for both pollutants) has a

[25] Normalised energy efficiency patent values are calculated by dividing by the total number of patents granted. This accounts for exogenous changes in patenting behaviour that affect all types of patents. Popp constructs a value for existing knowledge as the stock of previously granted patents, weighted by estimates that he derives for knowledge productivity. He demonstrates that the exclusion of this variable from the model leads to biased estimates for the energy price coefficient.

positive impact on its decision to invest in abatement equipment. However, the magnitude of the effect varies considerably across the sectors and is only significant for the iron and steel sector.

Frondel et al. (2008) analyse responses to an OECD survey on environmental policy tools (conducted in 2003) to identify the factors that affect a firm's decision to voluntarily adopt an environmental management system (EMS) and their environmental innovation behaviour. Innovation is captured by a binary variable that indicates whether the firm has "undertaken significant technical measures or changes to reduce the environmental impacts of production".[26] The analysis is based on survey responses from 899 firms in Germany. Latent variable equations for EMS adoption and innovation are estimated simultaneously, with each equation including the same four sets of variables – relating to motivations, policy instruments, pressure groups and facility characteristics.[27] The policy instrument variables include five dummy variables indicating the importance of different types of policy instrument, including market-based instruments such as emission taxes and tradable permits. While the perceived stringency of environmental policy is found to be a significant factor in the decision to innovate, there is no evidence that any of the individual policy instrument variables had any impact. The authors surmise that this suggests that it is stringency of environmental policy, rather than the choice of specific instrument, that is important for innovation. However, as the authors note, their results reflect the perceptions of the survey respondents and should therefore be treated as correlations rather than causal relationships.

Johnstone et al. (2009) assess the impact of a range of environmental policy instruments on innovation in the field of renewable energy. While they do not include environmental taxes in their evaluation, they do consider the impact of various price-based instruments including tax incentives (i.e. accelerated depreciation, etc.), investment incentives (e.g. low-interest loans, guarantees, etc.) and price-support policies (e.g. feed in tariffs and price guarantees). They analyse the impacts for five different groups of renewable energy technologies – wind, solar, geothermal, ocean, biomass and waste-to-energy – using a panel dataset of EPO[28] patent filings for these technologies across 25 countries over the period 1978-2003. A fixed effects negative binomial model is estimated, controlling for electricity prices and consumption, total EPO filings (as a proxy for differences / changes scientific capacity and patenting propensity) and the signing of the Kyoto Protocol (to capture expectations about future policy). Only public R&D expenditures, feed-in tariffs and renewable energy certificate (REC) targets are represented by continuous variables; the other policy instruments being represented by dummy variables indicating whether they were in place in a particular year. Consequently, for these variables, the model takes

---

[26] The next question on the survey asks whether these are changes in production processes or end-of-pipe technologies. However, no distinction is made between the two types of innovation in this study.

[27] In order to avoid identification problems, some individual variables are omitted from one equation or the other.

[28] European Patent Office.

no account of the stringency of the instruments – in particular the differing magnitudes of the tax measures and investment incentives.

Initially, the authors estimate the model with all of the policy instruments included individually. They find that public policy plays an important role in inducing innovation; with public R&D expenditure and the passage of the Kyoto Protocol both having a significant positive impact on patenting in renewable energy overall and specifically on patenting activity in wind and solar technologies. However, the impacts of the individual policy instruments vary considerably across the different technologies. In particular, while REC targets have a significant positive impact on innovation in wind and geothermal technologies, feed-in tariffs only have a significant impact on patenting activity in solar energy. This reflects the fact that the REC targets are generic and hence favour those technologies that are closest to market, while feed-in tariffs are technology-specific and thus can provide incentives for (currently) high-cost technologies.[29]

Of the policy instruments represented by dummy variables, investment incentives have a positive impact for all technologies except wind, but are only significant for geothermal and biomass (and solar at the 10% level). In contrast, neither tax measures, nor voluntary programmes, are found to have a significant impact on innovation for any of the technologies. To a certain extent, this may reflect a relative lack of stringency of these instruments (which is not captured by the dummy variables). However, the authors surmise that it may also reflect multi-collinearity between some of the policy dummy variables (particularly between investment incentives and tax measures) – making it impossible to isolate the respective impacts of these instruments.

De Vries & Medhi (2008) also use patent data to investigate the relative importance of environmental regulations and fuel prices on innovation in automotive emission control technologies, distinguishing between post-combustion devices and engine re-design technologies. They estimate a panel data model using data from the US, Japan and Germany over the period 1978-2001, controlling for industry value added (as a proxy for the scope of technological opportunities), and total patent applications (as a proxy for differences / changes in patenting propensity). Environmental regulation is represented by two dummy variables indicting the introduction of on-board diagnostic (OBD) regulations in the US.[30] The results of the analysis suggest that the relative impacts of regulation and market forces differ between the two types of technology. For post-combustion technologies, both of the regulations are significant, while fuel prices have no significant impact. In contrast, the opposite is the case for engine re-design technologies, with fuel prices having a significant impact, but regulation having no discernable effect. While the

---

29 For example, in 2004, the feed-in tariff in Germany for solar energy was five times greater than the respective tariffs for wind and geothermal.

30 Because of the international nature of the automotive industry and the importance of the US market, regulations introduced in the US appear to have been an important driver for innovation by overseas manufacturers. Regulations mandating the installation of OBD systems were first introduced in California in 1988. A more sophisticated system was mandated by the 1990 US Clean Air Act Amendments, taking force in 1996.

analysis does not explicitly consider the impact of fuel taxes, it suggests that increase in automotive fuel taxes would have a major impact on innovation in relation to engine design. The estimated coefficient for fuel prices (1.287) implies that a 10 US cent increase in fuel prices would induce a 14% increase in patenting activity.[31]

The empirical studies considered above cover a range of different technology areas – spanning energy efficiency (both product and process), renewable energy, and air and water pollution abatement. While in some cases, they assess the impact of energy prices rather than environmental taxes *per se*, they provide a clear picture of the likely impact of environmental and energy-related taxes on eco-innovation.

Three of the studies assess the impact on diffusion of existing technologies. All of these find that environmental taxes / energy prices have a positive impact on diffusion. In particular, the water effluent charges in The Netherlands appear to have had a major impact on the adoption of waste-water treatment equipment by the food and beverage industry in that country. However, there is some evidence to suggest that the effectiveness of taxes / prices may vary across sectors (e.g. NO_x / SO_2 abatement in France) and that investment incentives / subsidies may be more effective in some cases (e.g. thermal insulation in the US).

Three of the studies use patent data to assess the impact of environmental taxes and energy prices on innovation, with one of these also assessing the impact of investment incentives. All of these find a significant positive impact, although this depends on the particular sub-sector (e.g. renewable energy) and / or the type of innovation. In particular, the evidence from the automotive emissions control study suggests that taxes / prices may be more effective in promoting process-related innovation (e.g. engine re-design) than innovation in end-of-pipe technologies. One of the studies takes a different approach, using a product characteristics model to decompose improvements in the energy efficiency of consumer durables. This finds that while electricity prices did not appear to affect overall technological change (i.e. shifts in the product cost / energy efficiency frontier), they did have a positive impact on directional technological change (i.e. the slope of the frontier).

2.2.7 Case studies

Christiansen & Skjaerseth (2005) undertake a comparative analysis of the impacts of climate change policies on the petroleum sectors in Norway and The Netherlands during the 1990s. These countries were selected because of their very different policy approaches; with the Norwegian petroleum sector being subject to a CO_2 tax since 1991 (as part of a portfolio of measures[32]), while The Netherlands has relied on a series of voluntary

---

[31] The coefficient represents the semi-elasticity of patent applications with respect to fuel prices. While the authors do not state explicitly, the implication is that prices are expressed in US dollars (they are obtained from the IEA Energy Prices and Taxes Database). Consequently, the impact of a 10 US cent increase in the fuel prices is given by $\exp(1.287 \times 0.1) - 1 = 0.137$

[32] In addition to the tax, the portfolio included publicly-funded R&D support schemes, gas flaring permits and mandatory Environmental Impact Assessments

agreements on energy efficiency.[33] Both approaches appear to have been effective, in that CO_2 emissions per unit production fell by around 22% between 1990 and 2001 in Norway, while energy efficiency improved by around 35% in The Netherlands over the same period. However, there were marked differences between the tow countries in terms of the nature of the innovation that occurred. In The Netherlands, technological change was incremental, reflecting a steady diffusion of available (i.e. known) technology. In contrast, the authors find evidence of more radical innovations and adaptations by the Norwegian petroleum sector – including the development of energy-efficient gas turbines, installation of waste heat recovery units, process modifications and improved utilization of process heat. While the authors acknowledge the impossibility of proving a causal link between policy intervention and innovation (in the context of their case study), they conclude that the CO_2 tax played a key role in the development and implementation of these radical innovations; with the benefits of reduced tax payments providing an important incentive. However, they also conclude that the impacts of the two instruments were conditioned by the political contexts in which they were applied and the problem characteristics in the respective countries (e.g. the economic significance of the sector, size of installations, etc.).

Knigge & Görlach (2005) summarize the findings of a comprehensive analysis of the impacts of the ETR in Germany that was undertaken jointly by Ecologic and the German Institute for Economic Research (DIW Berlin) – including the impacts on innovation and market diffusion of environmentally friendly products and technologies.[34] Based on a series of case studies, the study concluded that the ETR had a “noticeable effect” on innovation and diffusion, although it was not possible to quantify the scale of that effect. In particular, the ETR is identified as being a central factor in the development of gas-powered vehicles. The study identifies a number of different routes by which the impacts of the ETR occurred. First, the payback period for energy efficient products was reduced as a result of the energy tax increases and the various exemptions favouring efficient energy use and renewable energy sources. Second, the predictable nature of the energy taxes (as opposed to widely fluctuating oil prices) reduced uncertainties about the benefits of energy efficiency investments. Third, the reduction in employers’ social contribution payments tended to reduce the costs of labour intensive innovation processes – such as research and development, energy consultancy and technology installation. Finally, the ETR had a signaling effect, strengthening awareness of the need for more efficient and rational energy use.

Mickwitz et al. (2008) examine a number of “claims” that have been made in the environmental policy literature about the relationship between policy instruments and

[33] The Dutch oil and gas industry first signed a Declaration of Intent with the government in 1995. This was translated into a Long Term Agreement (LTA) on energy efficiency in the following year, with an improvement target of 20% over the period 1989-2000. In 2001, a new LTA was signed which committed firms to implementing energy efficiency measures with a positive NPV at a 15% discount rate or a five year payback period.

[34] A separate report in German by *Görlach et al.* (2005) provides details of the evaluation of the innovation and diffusion impacts.

innovation, based on experiences in two industrial sectors in Finland: pulp and paper and the manufacture of diesel engines for ships. In particular, they assess the claims that "environmental taxes are superior to other policy instruments with respect to innovation" and that "R&D subsidies have limited impacts on innovation". With respect to the first claim, the evidence provided by the two case studies is mixed. The authors conclude that energy taxation had a negligible impact on innovation in the pulp and paper industry. However, this is likely to have been due to the low level of the tax and the exemptions that applied to the sector. In contrast, they find that the differentiation of Swedish fairway and port fees (on the basis of SO_2 and NO_X emissions) was a significant factor driving the installation of in-engine NO_X reduction equipment in ferries operating between the two countries.[35] With respect to R&D subsidies, the authors conclude that the evidence does not support the claim that these have little effect. In particular, they find that R&D subsidies accelerated the development of ship engine emissions reduction technologies.

The findings of the three case studies are consistent with those of the empirical analyses reviewed in the previous section. Environmental taxes and investment subsidies have proved significant in promoting both innovation and diffusion, although not universally so. Furthermore, the case studies provide some useful insights about the ways in which the impacts occur and the factors that may be important in promoting innovation. In particular, they suggest the need for a tax rate that is sufficiently high to provide a meaningful incentive and signaling effect, and that is fixed for a sufficiently long period of time to reduce uncertainty about the future benefits of investment.

2.2.8 Conclusions

The studies reviewed in the preceding sections suggest that environmental regulation in general, and price-based policy instruments such as environmental taxes and investment subsidies in particular, can (in theory) and do (in practice) have a positive impact on both innovation and diffusion of environmental technologies. However, the supporting empirical and case study evidence is not universal and the effectiveness of these instruments would appear to vary across different sectors and different types of innovation.

To a certain extent, such differences can be explained by the theoretical models. In particular, the impact of environmental taxes (relative to other instruments) is predicted to depend on the competitive structures of the markets in which the regulated firms operate and on the ability of innovator firms to appropriate the benefits accruing to other firms during diffusion. However, a number of other potential factors have been identified in the literature which may affect the impact of price-based policy instruments on innovation.

Jaffe et al. (2002) caution that the impact of price-based policy instruments on technology diffusion may be adversely affected by a number of potential market failures, including information failures, principle-agent problems (e.g. landlord-tenant), capital

[35] Although the tax was introduced in Sweden, it was also payable by Finnish ferry operators entering Swedish ports and hence affected their investment decisions. This is another example of the cross-border impact of environmental policy interventions on innovation found by *Lanjouw & Mody* (1996) – see section 3.1.

market failures and positive adoption spillovers. In addition, while not market failures as such; uncertainty over future returns and the (associated) use of high discount rates for investment decisions can also undermine the effectiveness of price-based instruments in stimulating diffusion. However, as was noted above, the findings from the case study of the ETR in Germany suggest that an environmental tax may actually reduce the level of uncertainty over future returns provided that it is of sufficient magnitude and longevity.

Skjaerseth & Christiansen (2005) emphasize that the relationship between policy instruments (of all types) and technological change is extremely complicated. They argue that account must be taken of the political / industrial context in which policy instruments are introduced, and the nature of the environmental problem that they are intended to address. In particular, they make a distinction between "malign problems" where technological change involves net costs for target groups, and "benign problems" where there are widespread "no-regret" opportunities for change. Based on a comparative analysis of four different case studies, they conclude that mandatory policy instruments (including environmental taxes) are more effective in promoting short-term technological change when the problems are malign, but that low legitimacy (with the target group) may undermine long-term technological change. However, when problems are benign, or when long-term change requires cooperation, voluntary policy instruments are likely to be more effective.

Johnstone (2005) questions the focus of the theoretical and empirical analyses (reviewed above) on the impact of environmental policy instruments on the rate of technological change; arguing that the direction of technological change is as important – if not more so. It is not just the quantity of innovation that is important. It is also important that innovation is socially-optimal in the sense that it minimizes the cost of attaining a particular environmental goal in the long term. Inappropriate innovation today may result in "lock-in" to a sub-optimal technological path for the future.

With this in mind, he identifies a number of issues that can adversely affect the direction of innovation, and that should be taken into account when selecting and designing policy instruments: technological market failures[36]; missing markets for certain environmental attributes of innovation; policy incidence; and joint production of emissions. Most studies of the innovation effects of environmental policy instruments assume that the only missing market is that for the environmental good (bad). However, in practice there may be other markets that are missing (or incomplete), which can adversely affect transmission of innovation incentives. This is particularly so in the area of waste / resource management, where instruments applied at the end of the product lifecycle may have little or no impact on product design innovation. Even if all markets are complete except for the environmental externality, the point of incidence of the policy intervention may be more important for the direction of innovation than the choice of particular policy instrument. For example, a limit or standard applied directly to the emissions of a pollutant may be more effective in promoting optimal innovation than a tax applied to a proxy input variable. Finally, when there is joint production of pollutants (e.g. CO_2 and air pollutants

[36] These are the same market failures that are identified by *Jaffe et al* (2002)

from vehicle engines), there is a danger that if policy instruments (of whatever type) are applied to one pollutant in isolation, the resultant innovation may reduce emissions of that pollutant at the expense of increases in the others.

In a related point, he highlights the importance of using appropriate indicators when assessing the impact of policy instruments on innovation; emphasizing the need for these to reflect both the rate of innovation and the direction. A necessary condition for this is that the indicators must provide an accurate and detailed picture of actual innovation. Unfortunately, this is difficult to achieve in practice. For example, the use of patent data as a measure of innovation requires the identification of relevant environmental technologies. This is likely to be easier for end-of-pipe technologies than for process-related technologies, meaning that the latter tend to be under-represented relative to their actual incidence. To the extent that process-related innovation is growing in importance, or is more important for certain sectors or types of environmental problem, changes in the value of the indicator may significantly understate the actual rate of innovation and misrepresent the direction.

All of this suggests that caution should be exercised in drawing general, definitive conclusions about the impacts of price-based policy instruments such as environmental taxes and investment subsidies on innovation – particularly relative to other policy instruments. While it would appear that they can be effective in stimulating both innovation and diffusion in many cases – at least in terms of the rate of technological change, there may be situations in which other policy instruments may be more appropriate. In general, the stringency and point of incidence of an environmental policy intervention may be more important than the choice of a particular policy instrument in determining the rate and direction of eco-innovation.

3 THE GINFORS MODEL

The simulation instrument – the global model GINFORS (**G**lobal **IN**terindustry **FOR**ecasting **S**ystem) – describes the economic development, energy demand, CO_2 emissions and resource inputs for 50 countries, 2 regions, 41 product groups, 12 energy carriers and 9 resources. The regions are “OPEC” and “Rest of the World”. The explicitly modelled region “OPEC” and the 50 countries cover about 95% of world GDP and 95% of global CO_2 emissions. The aggregated region “Rest of the World” is needed for the closure of the system. The model is documented in Meyer et al. (2007), Meyer & Lutz (2007) and Lutz et al. (2010). Current applications of the model can be found in Giljum et al. (2008) and Lutz & Meyer (2009a, 2009b). An update of the material models is provided in Lutz & Giljum (2009). The related German model PANTA RHEI has been applied to endogenize technological change in a few industry sectors as iron and steel and paper (Lutz et al., 2005).

The main difference to neoclassical CGE models is the representation of prices, which are determined due to the mark-up hypothesis by unit costs and not specified as long run competitive prices. But this does not mean that the model is demand side driven, as the use of input-output models might suggest. Even though demand determines production, all demand variables depend on relative prices that are given by unit costs of the firms using the mark-up hypothesis, which is typical for oligopolistic markets. The difference between

CGE models and GINFORS can be found in the underlying market structure and not in the accentuation of either market side. Firms are setting the prices depending on their costs and on the prices of competing imports. Demand is reacting to price signals and thus determining production. Hence, the modeling of GINFORS includes both demand and supply elements.

Allowance prices and carbon tax rates are endogenous to the model. To avoid long solving procedures, the prices are changed in an iterative process manually until the GHG reduction target is reached. Allowance prices increase the shadow prices of energy carriers and reduce energy demand according to the specific price elasticities. Different allocation methods therefore have no direct influence on energy demand and the emission levels in the model. But increasing profits of private companies in the case of grandfathering deliver other macroeconomic impacts than government spending out of auctioning revenues.

All parameters of the model are estimated econometrically, and different specifications of the functions are tested against each other, which gives the model an empirical validation. An additional confirmation of the model structure as a whole is given by the convergence property of the solution which has to be fulfilled year by year. The econometric estimations build on times series from OECD, IMF and IEA from 1980 to 2006. For a number of variables the data were only available for a shorter time period. The modelling philosophy of GINFORS is close to that of INFORUM type modelling (Almon, 1991) and to that of the model E3ME from Cambridge Econometrics (Barker et al., 2007a). Common properties and minor differences between E3ME and GINFORS are discussed in Barker et al (2007b).

4 Scenarios

To investigate the impacts of an ETR for Europe six separate scenarios have been designed in the petrE project to understand a variety of tax reform options. Each scenario is identified by an acronym. The final letter indicates the baseline to which it is compared with L for low energy prices and H for high energy prices.

The scenario analysis allows for an understanding of different revenue recycling methods and various scales of ETR in order to meet different greenhouse gas emissions targets. All scenarios were examined in both E3ME and GINFORS. The scenarios are:

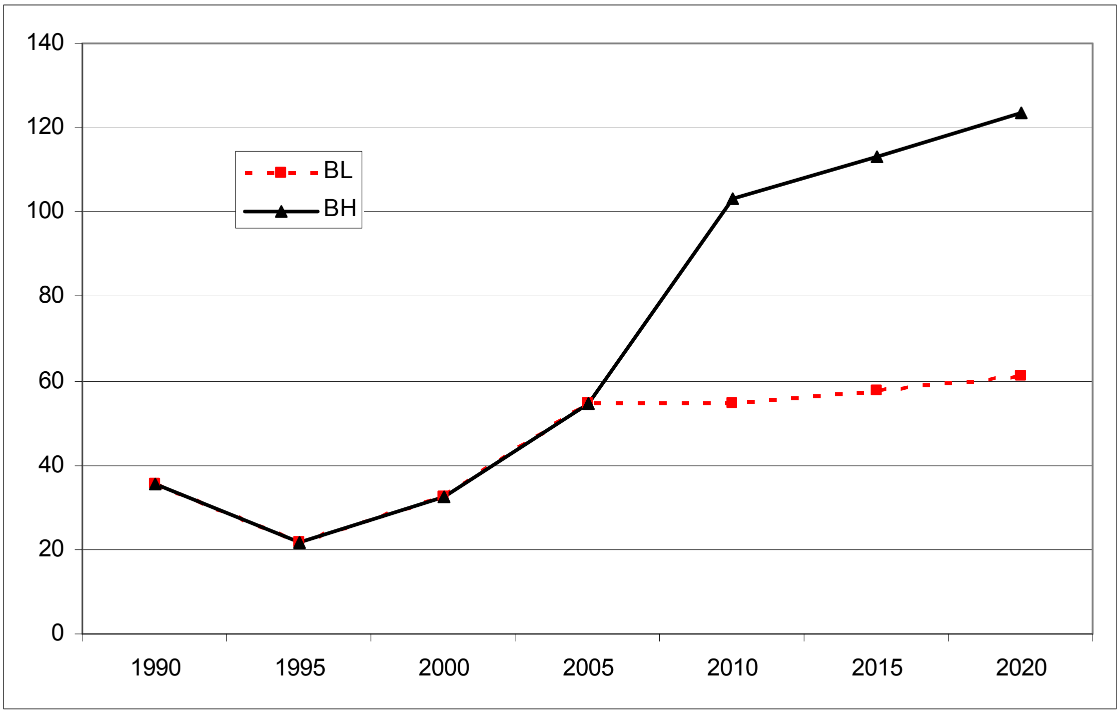
- BL: Baseline (low energy prices),
- BH: Baseline sensitivity with high oil price (reference case),
- Scenario S1L: ETR designed to meet unilateral EU 2020 GHG target with revenue recycling,
- Scenario S1H: ETR designed to meet unilateral EU 2020 GHG target (high oil price) with revenue recycling,
- Scenario S2H: ETR designed to meet unilateral EU 2020 GHG target (high oil price) with revenue recycling, 10% of revenues are spent on eco-innovation measures,
- Scenario S3H: ETR designed to meet EU 2020 GHG target with international cooperation (high oil price) with revenue recycling.

The baseline with low energy prices BL has been calibrated to the 2007 PRIMES baseline to 2030, published by the European Commission (DG TREN, 2008). For the high oil price baseline (reference case BH) the effect of a higher oil price, particularly over the period 2008-10 is assumed. In this scenario coal and gas prices develop in line with the increases to the oil price. In this scenario energy prices are close to the assumptions in the current IEA World Energy Outlook (2008).

Each of the ETR scenarios has the same key taxation components:

- a carbon tax rate is introduced to all non EU ETS sectors equal to the carbon price in the EU ETS that delivers an overall 20% reduction in greenhouse gas emissions by 2020, in the international cooperation scenario this is extended to 30%,
- aviation is included in the EU ETS at the end of Phase 2,
- power generation sector EU ETS permits are 100% auctioned in Phase 3 of the EU ETS,
- all other EU ETS permits are 50% auctioned in 2013 increasing to 100% in 2020,
- material taxes are introduced at 5% of total price in 2010 increasing to 15% by 2020.

Figure 1: International oil price in the two scenarios in $2005/b



In scenarios S1L, S1H and S3H environmental tax revenues are recycled through reductions in income tax rates and social security contributions in each of the member states, such that there is no direct change in tax revenues. In scenario S2H 10% of the environmental tax revenues are recycled through spending on eco-innovation measures, the remaining 90% is recycled through the same measures as in the other scenarios. The eco-innovation spending is split across power generation and housing according to tax revenues from the corporate and household sector. In GINFORS the share of renewable sources in electricity production is increased due to the additional investment. The rest of additional investment goes to household energy efficiency spending. Investment needed for a certain increase in RES or efficiency improvement is based on German and Austrian experience (Lehr et al., 2008 and 2009, Grossmann et al., 2008, Lutz & Meyer, 2008). This assumption is quite conservative as parameters for other countries can be assumed to be more positive (less money needed for renewable energy technology installation or energy efficiency gains).

In scenarios S1L and S1H the 20% GHG target translates into a 15% reduction of energy-related carbon emissions against 1990 as other emissions such as methane and nitrous oxide already have been reduced above average. The target is reached by a tightened EU ETS cap and the introduction of a carbon tax on the non-ETS sector. The tax rate applied is equal to the carbon price in the EU ETS that will deliver 20% reduction in GHG by 2020.

ETR tax will be allotted to energy outputs, i.e. the final use of energy, and will be based on the carbon content of each fuel. Carbon prices are assumed to be fully passed on to consumers. All carbon taxes will be in addition to any existing unilateral carbon and energy taxes. The carbon reductions in the different EU Member States (MS) will be those that the same carbon tax increase across the EU produces.

100% of the revenues, including EU ETS auctioning revenues, carbon tax revenues and material tax revenues will be recycled. The proportion of tax raised by industry will be recycled into a reduction in employers' social security contributions, which will in turn reduce the cost of labour. Recycling will be additional to the existing ETRs in some member states. Revenues raised from households will be recycled through standard rate income tax reductions. Traditional energy tax revenues will be lower compared to the respective baseline, as the tax base (energy consumption) is reduced. So revenue-neutrality does not mean budget-neutrality of an ETR.

Table 1: International energy prices in the two baseline scenarios

	EU: Energy import prices in $ (2005) / boe			EU: Energy import prices in $ /boe		
	Baseline BL			Baseline BL		
Year	Oil	Gas	Coal	Oil	Gas	Coal
1990	35.5	35.5	16.9	-	-	-
1995	21.8	16.7	13.5	-	-	-
2000	32.3	32.4	8.9	-	-	-
2005	54.5	40.1	14.8	54.4	40.1	14.8
2010	54.5	43.3	13.7	60.0	47.7	15.1
2015	57.8	45.8	14.3	70.8	56.1	17.5
2020	61.1	48.9	14.7	83.4	66.8	20.1
	Baseline BH			Baseline BH		
Year	Oil	Gas	Coal	Oil	Gas	Coal
2010	103.1	81.9	25.9	113.5	90.2	28.5
2015	113.2	89.7	28.0	138.6	109.8	34.2
2020	123.5	98.8	29.7	168.6	134.9	40.6

Scenario S3H is used to investigate the effect that international cooperation would have on competitiveness and resources. In this scenario we assume that the rest of the world takes action towards reducing carbon emissions. International action is expected to reduce the loss of competitiveness the EU would face if it embarked on unilateral action. However, in this scenario, the tax levied is larger and is designed to reduce greenhouse gas emissions by 30% in 2020, rather than 20% in the preceding scenarios.

Scenario S3H leans on scenario S1H but with higher targets in line with the EU's stated policy objective of a 30% GHG reduction against 1990 until 2020. In GINFORS ETS and ETR is modelled in the major OECD countries. CO_2 prices in these countries are equal to EU prices. Emerging economies will introduce a CO_2 tax recycled via income tax reductions. CO_2 tax rates will be 25% of EU (OECD) prices in 2020. Restricted participation of emerging economies takes into account shared but differentiated responsibility (lower historic burden, lower GDP per capita) based on a post-Kyoto project for the German Ministry of Economy in 2007 (Lutz & Meyer, 2009a). The 30% reduction will be in European emissions, without trying to take account of JI/CDM transactions that could be on top of the extra EU carbon reduction.

Earlier analyses (Lehr et al., 2008, ISI et al., 2009, Boira-Segarra, 2004, Kammen et al., 2004, Moreno and López, 2007) studied the impacts of large shares of RES in the energy mix for different countries. The overall question in these studies has been the impact of increasing RES shares on the economy, especially on the labour market. For the scope of our work here it is interesting to note that macroeconomic impacts of higher RES shares mainly depend on

(1) additional investment in RES (minus lower investment in conventional, i.e. fossil and nuclear power) obviously even more so if a country has the respective industry
(2) additional (net) exports due to better international competitiveness for RES (first mover advantage),
(3) lower fossil fuel needs,
(4) the cost differences between RES and conventional energy and
(5) the shift from capital- and energy-intensive industries to labour- and technology-intensive industries

which all are driven by international energy prices, carbon prices, the policy framework and the RES technology development itself. Innovation comes into the play at various stages: Firstly, innovation drives the currently positive additional costs of RES technologies down and into the negative realms, depending on the respective fossil fuel scenario. Secondly, innovative products increase the competitive advantage of products on the international markets. Though a fair share of the RES technology production in Europe is traded in Europe, innovation will still provide an edge on current and emerging international markets. The EmployRES study (ISI et al., 2009) finds for Europe that currently the strong investment impulses - based on installations in Europe and exports to the rest of the world - dominate the economic impact of RES policies and therefore lead to positive overall effects. The results in the study suggest that this positive balance can only be kept up in the future, if the competitive position of European manufacturers of RES technology is even improved: The authors strongly recommend "policies which promote technological innovation in RES and lead to a continued and rapid reduction of their costs".

(1) and (2) will have substantial impacts in the short and medium-term, whereas (3) adds up and will show positive stock impacts mainly in the long-term. (4) strongly depend on the global development. (5) may have significant effects on employment.

Impacts of additional investment (1) have already been analysed in scenario S2H of the petrE project. To focus on the impacts of eco-innovation two additional scenarios have been designed, that build on scenario S2H of the petrE project:

- S2HE: ETR with revenue recycling designed to meet the unilateral EU 2020 GHG target (high oil price), 10% of revenues are spent on eco-innovation measures, trade shares of EU-27 economies with the rest of the world in machinery and electrical machinery increase by .1% due to the deployment of the fast growing RES markets. This assumption is based on the strong EU policy effort to increase the share on renewable energy in final energy consumption to 20% by 2020 (ISI et al., 2009) and the possibility of very strong world market development of the RES until 2020 (EREC 2008), which offers additional export opportunities for European RES industries.
- S2HI: ETR with revenue recycling designed to meet the unilateral EU 2020 GHG target (high oil price), 10% of revenues are spent on eco-innovation measures, input structures of the utility sector are changed according to the input structure of the German RES industry (Lehr et al., 2008).

S2HE looks at the possible role of international trade, S2HI analyses changing in the input structure of the utility sector, i.e. from conventional electricity production to renewables. In the petrE project (as in GHK et al., 2007) only the energy inputs of the utility sector had been adapted to changes in the energy input mix.

Both scenarios focus on RES and efficiency technologies. As mentioned above, an ETR will trigger a variety of innovations as such. Therefore the results can be thought of as conservative in the sense that innovations e.g. on automotive energy consumption, industrial efficiency, community efforts etc. are not included explicitly.

5 Overview of modelling results

The main results of the simulations are highlighted in Table 2. High energy price scenarios are in the centre of the discussion. They are close to medium and long-term price expectations of the IEA (2008). In the baseline scenario BH with high energy prices, EU-27 carbon emissions will be 7.2% below 1990 level in 2020. EU-15 has committed in the Kyoto protocol to reduce its GHG emissions 8% below 1990 levels in the period 2008-2012. As emissions in the new member states are substantially below their 1990 levels today, EU-27 will keep its emissions more or less constant over the coming decade. As in the PRIMES baseline an ETS price of 18 Euro/t in 2008 prices is assumed in 2020.

Table 2: Main results in the different scenarios

Scenario	Target in 2020	CO_2 price	GDP		Employment	CO_2 reduction	
		Euro2008/t	pc against baseline		pc against baseline	pc against 1990	pc against baseline
	in year	2020	2015	2020	2020	2020	2020
BH		18				-7.2	0.0
S1H	20% GHG	68	-0.22	-0.57	0.36	-15.1	-8.4
S2H	20% GHG	61	-0.13	-0.30	0.41	-15.2	-8.5
S2HE	20% GHG	61	-0.09	-0.04	0.51	-15.1	-8.4
S2HI	20% GHG	61	-0.06	-0.24	0.45	-15.2	-8.4

In scenario S1H the ETS price and carbon tax rate has to be increased to 68 Euro2008/t of CO_2 to reach the 20% GHG reduction target, which is equal to a 15% reduction of CO_2 emissions against 1990 as other greenhouse gases have already been reduced above average. Compared to the baseline, CO_2 emissions are 8.4 % lower in 2020 which means an additional 1% p.a. reduction in the period 2012 to 2020. GDP will be about 0.6% lower compared to the baseline in 2020. This means that annual average growth rates will be less than 0.1% below their baseline development. This is especially low compared to the current financial and economic crisis, with a GDP deviation against the baseline of around 6% in 2009.

As the recycling mechanism reduces labour costs and the tax burden is shifted from labour-intensive to carbon- and material-intensive sectors employment will be 0.36% (or more than 800.000 jobs) higher than in the baseline. The ETR is not fully budget-neutral for the EU economies that can slightly increase their net savings. If this extra saving is spent, negative GDP impacts will be further reduced.

If part of the revenues is used for investment in low-carbon technologies, the carbon price in scenario S2H can even be lower (61 Euro2008/t in 2020) and the GDP loss halved against scenario S1H to only 0.3%, as the investment in renewable energies is assumed to be additional. Employment impacts will be more positive than in scenario S1H. The 10% investment in low-carbon technologies will amount to more than 20 Bill. Euro in 2020. The Obama administration currently plans to invest 15 Bill. US-Dollar p.a. in that area in the next four years.

If we assume additional EU exports of RES technologies in scenario S2HE, GDP could be almost the same as in the baseline in 2020. Employment will be 0.51% (or more than 1 mill. jobs) higher than in the baseline. A shift in the input structure of the utility sector towards machinery and electrical machinery, that reflects the different nature of RES in relation to conventional electricity generation, has also smaller additional positive impacts on GDP and employment compared to scenario S2H.

The following figures show impacts of the different scenarios in comparison to the baseline BH. According to Figure 3 GDP is slightly lower. The comparison of scenario S1H with the other 3 scenarios shows that additional RES investment (S2H), additional RES exports (S2HE) and the inclusion of different input structures of the RES industries (S2HI) have per se positive GDP impacts. Both results are in line with model-based analysis in the EMPLOY-RES study (ISI et al., 2009).

In contrast to GDP, employment increases in all scenarios (Figure 4). Due to the scenario design the structure of the EU economies is shifted from energy-intensive to labour-intensive sectors. The magnitude of the employment gain is influenced by the carbon price and the tax shift, the underlying energy prices and the production loss. The largest part of the employment increase stems from the ETR (scenario S2), whereas a shift in industry structures (S2HI) and additional RES exports (S2HE) are both positive for the labour market but less important. As ETR is directly targeting labour costs, it is better suited to create additional jobs than positive effects of eco-innovation on the industry structure or export markets.

Figure 2: GDP of EU-27 in Bill. US-Dollars (PPPs) in prices of 2005 in different scenarios

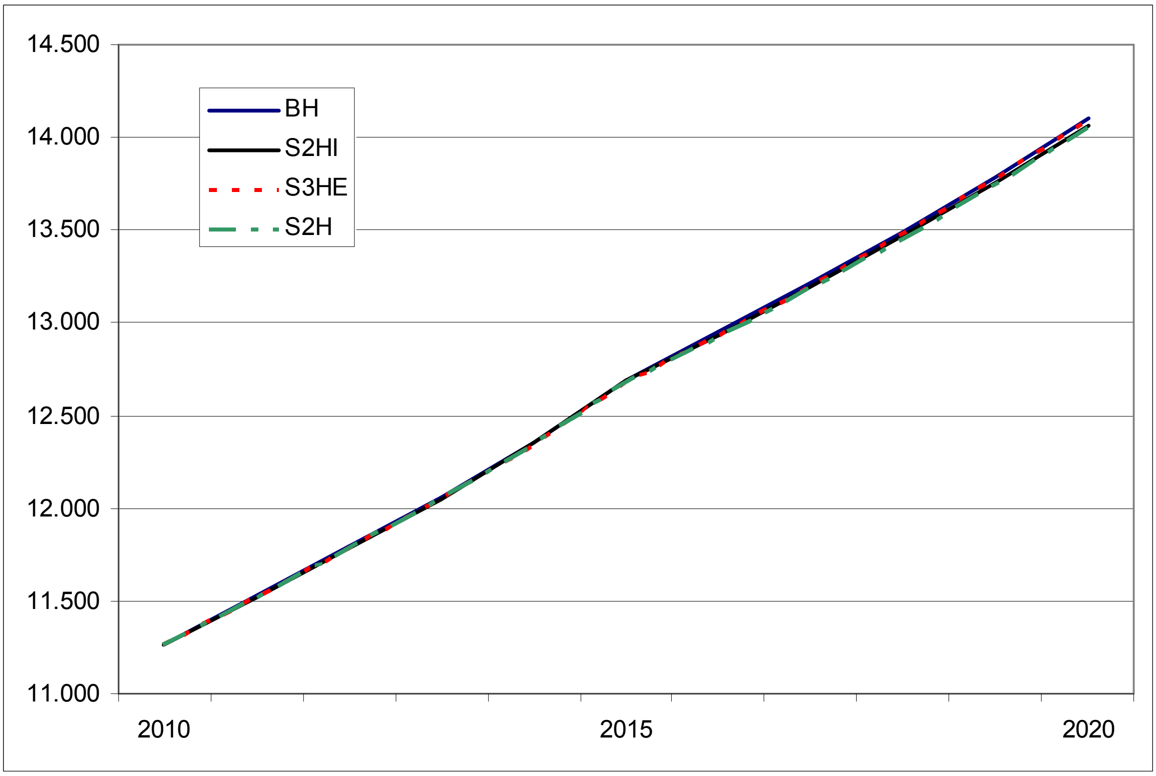


Figure 3: GDP of EU-27 in Bill. US-Dollars (PPPs) in prices of 2005 in different scenarios - percentage deviations against the baseline BH

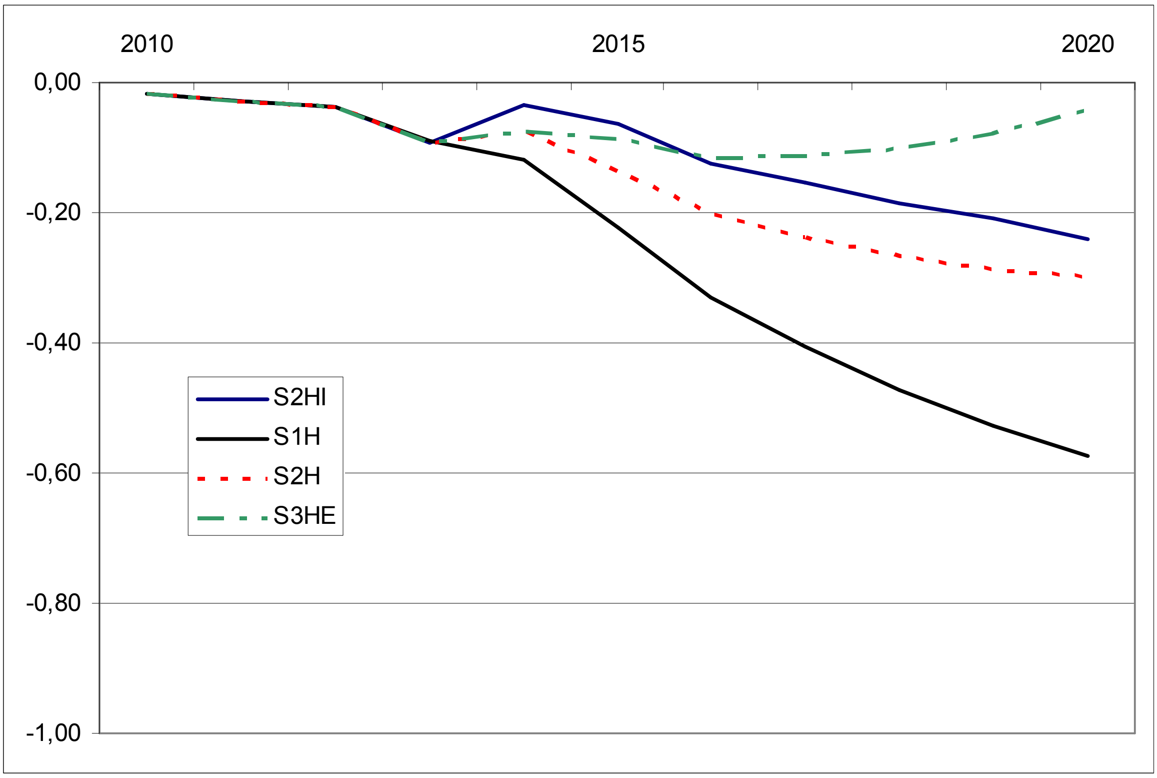
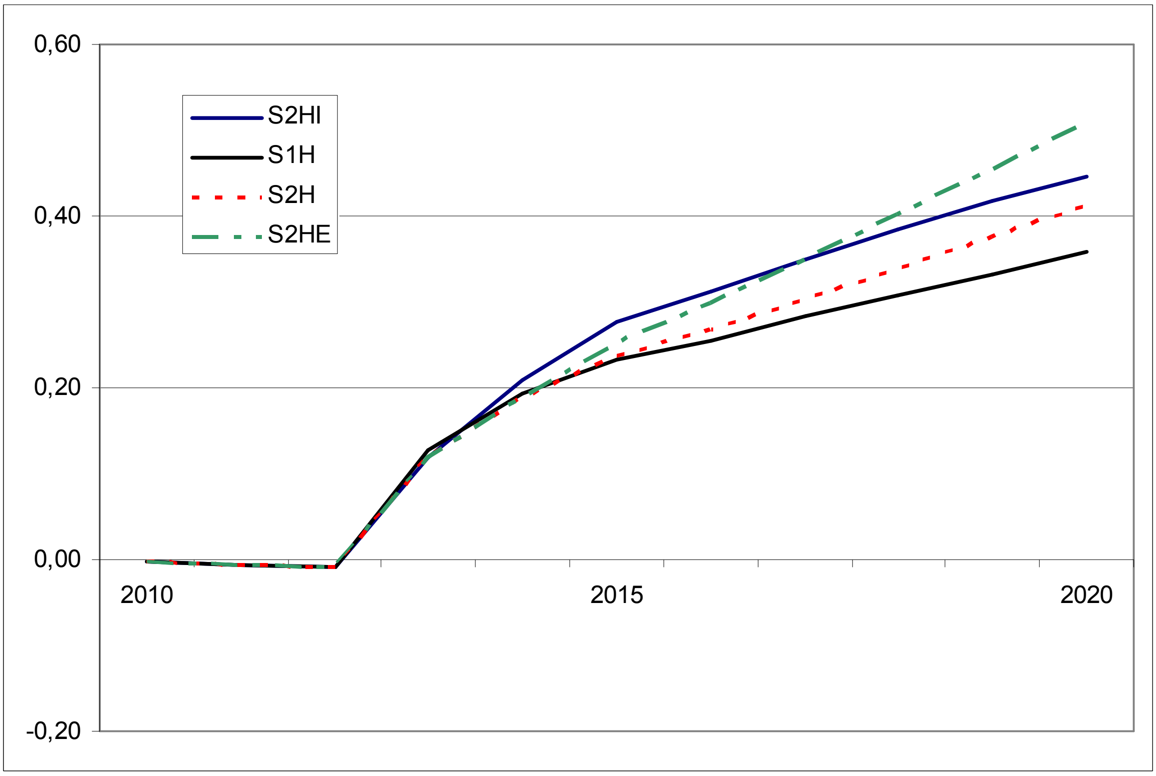


Figure 4: Employment in EU-27 in 1000 in different scenarios - percentage deviations against the baseline



6 Results of scenario S2H

The impacts of the modelled ETS and ETR on country level strongly depend on country specifics including energy use, economic structure and different social systems and behaviour, e.g. reactions to labour cost changes. In countries with high carbon intensity additional revenues and expenditures are higher than in countries with lower carbon intensity. Revenues in the UK are below EU average, which is one important reason, why impacts on the UK are quite low. Countries with high emissions in the ETS sector such as Germany and most of the new member states will raise a lot of money when auctioning the emission rights that is used for reducing labour costs and for additional RES and efficiency investment, which partly explains positive impacts on the labour market. The relevance and opportunities of additional revenues have not yet been fully perceived by policy makers.

Impacts of scenario S2H are between 0 and -1% of GDP in 2020 for the large EU economies with the exception of Italy (Figure 6). Germany can even keep its GDP due to its strong RES industry. Other countries in the world slightly gain competitiveness against EU countries, as export prices in most EU countries and sectors increase (Figure 5). This is mainly due to the fact, that carbon tax revenues are recycled back via income tax reductions which are not part of production costs. Energy exporting economies such as Russia or South Africa will lose exports, if EU energy demand declines.

Employment impacts of scenario S2H are positive for almost all EU countries, as lower labour costs increase labour demand and labour intensity (Figure 7). The highest absolute increases are shown for Germany, the Netherlands, Italy and the UK. For EU-27 as a whole, employment will be almost 1 mill. higher than in the corresponding baseline BH in 2020. It is also worthwhile to note, that the economic impacts of higher energy prices itself will be much higher (Ekins and Speck, 2010).

Figure 5: GDP in 2005 prices in selected countries: percentage deviations of scenario S2H against baseline BH in 2020

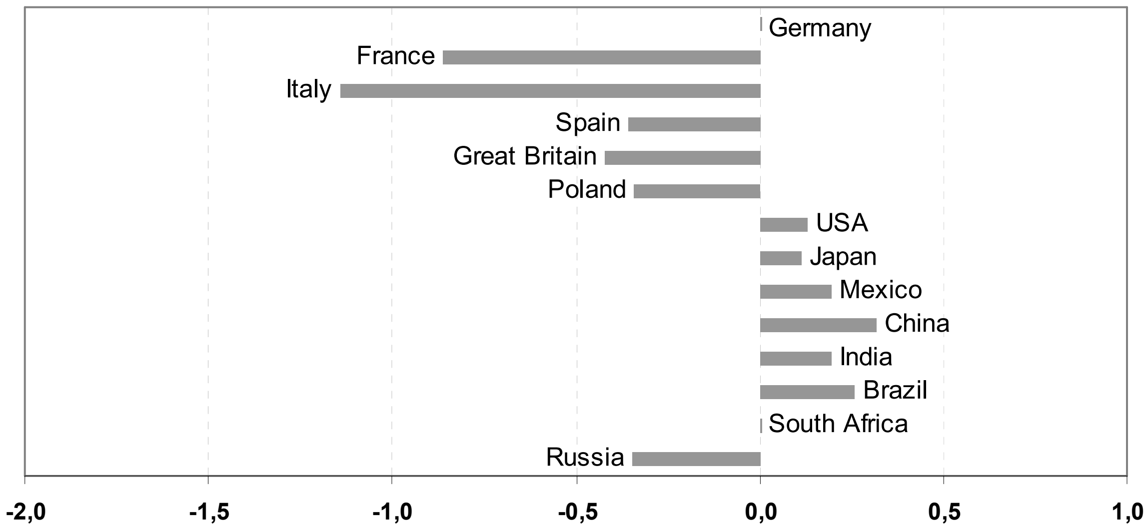


Figure 6: GDP in 2005 prices in EU-27: percentage deviations of scenario S2H against baseline BH in 2020

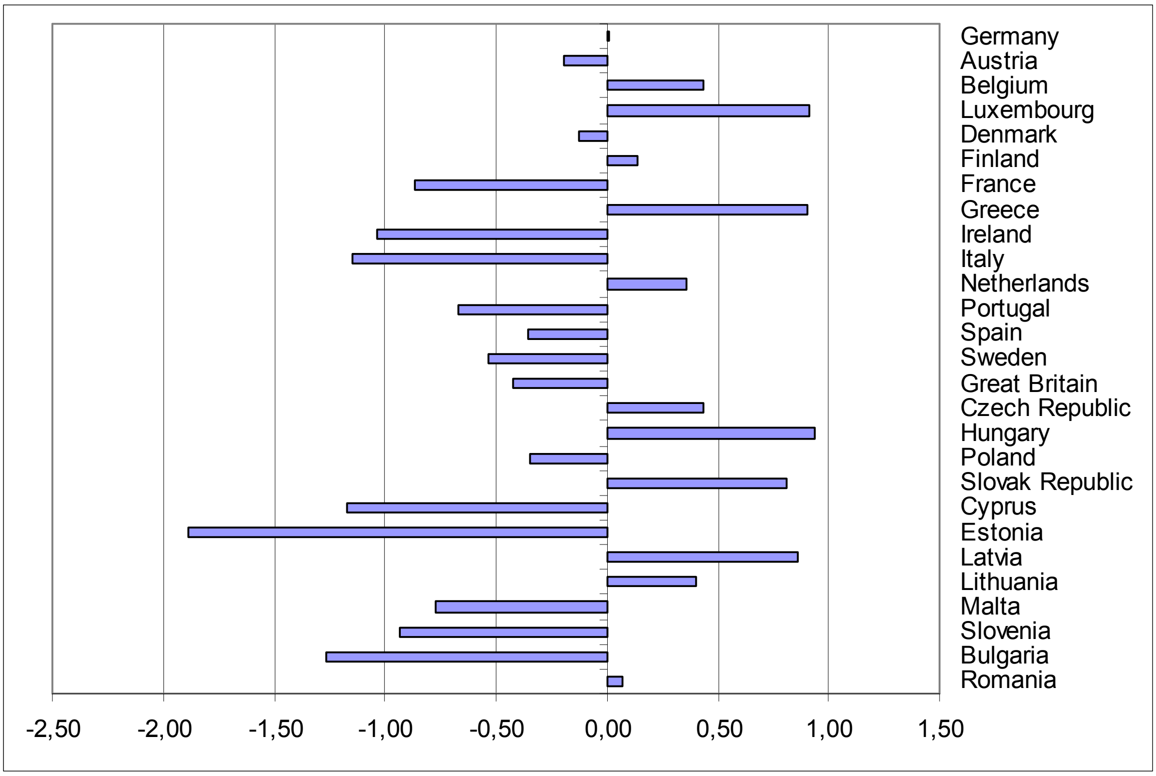


Figure 7: Employment in 1000 in EU-27: deviations of scenario S2H against baseline BH in 2020

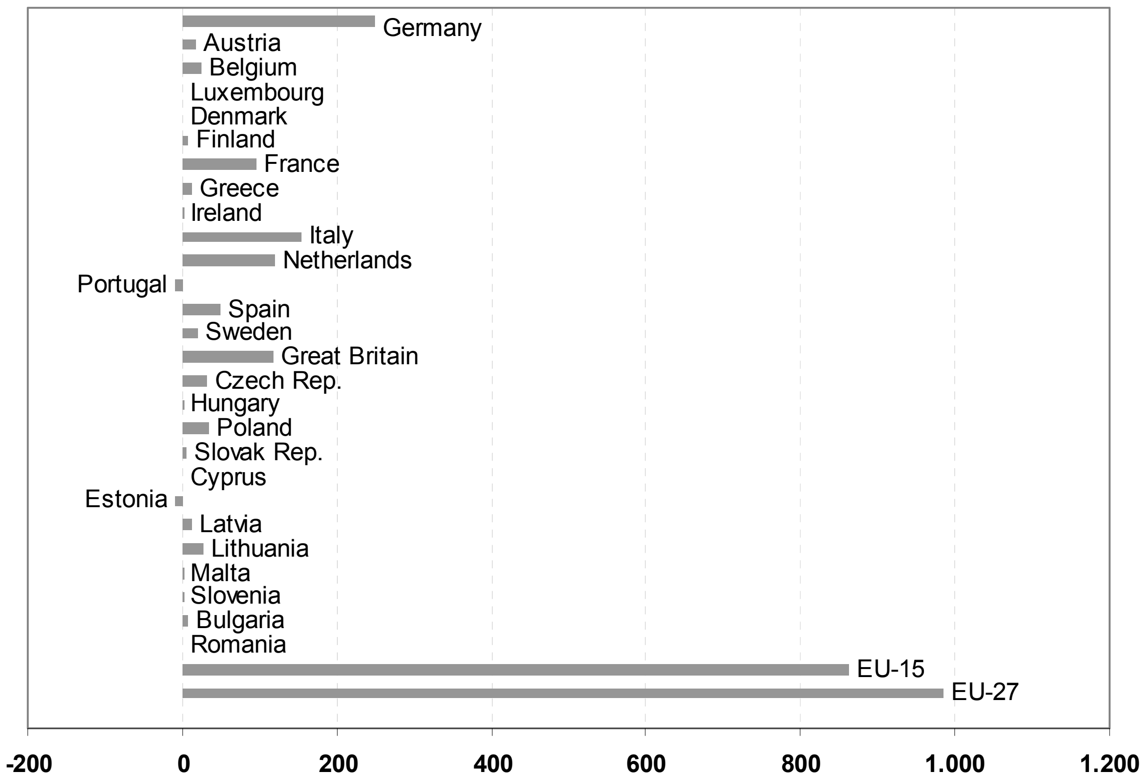


Figure 8: Energy-related CO_2 emissions in Mt: percentage deviations of scenario S2H against baseline BH in 2020

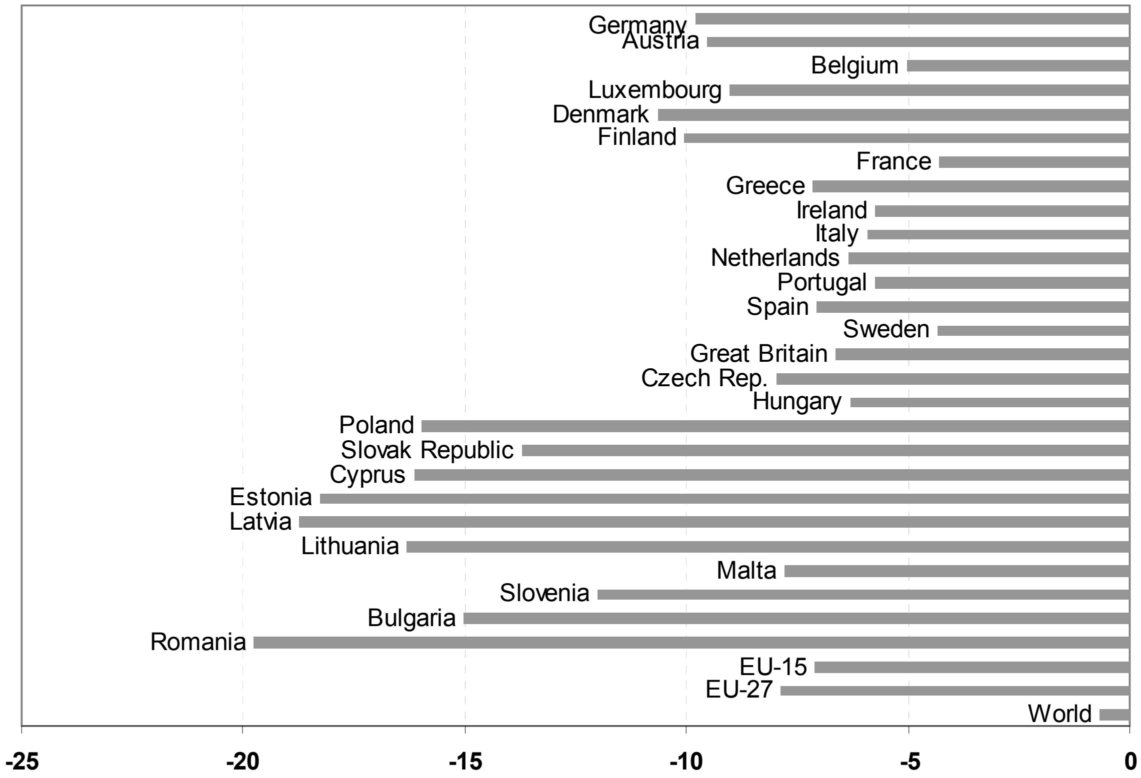
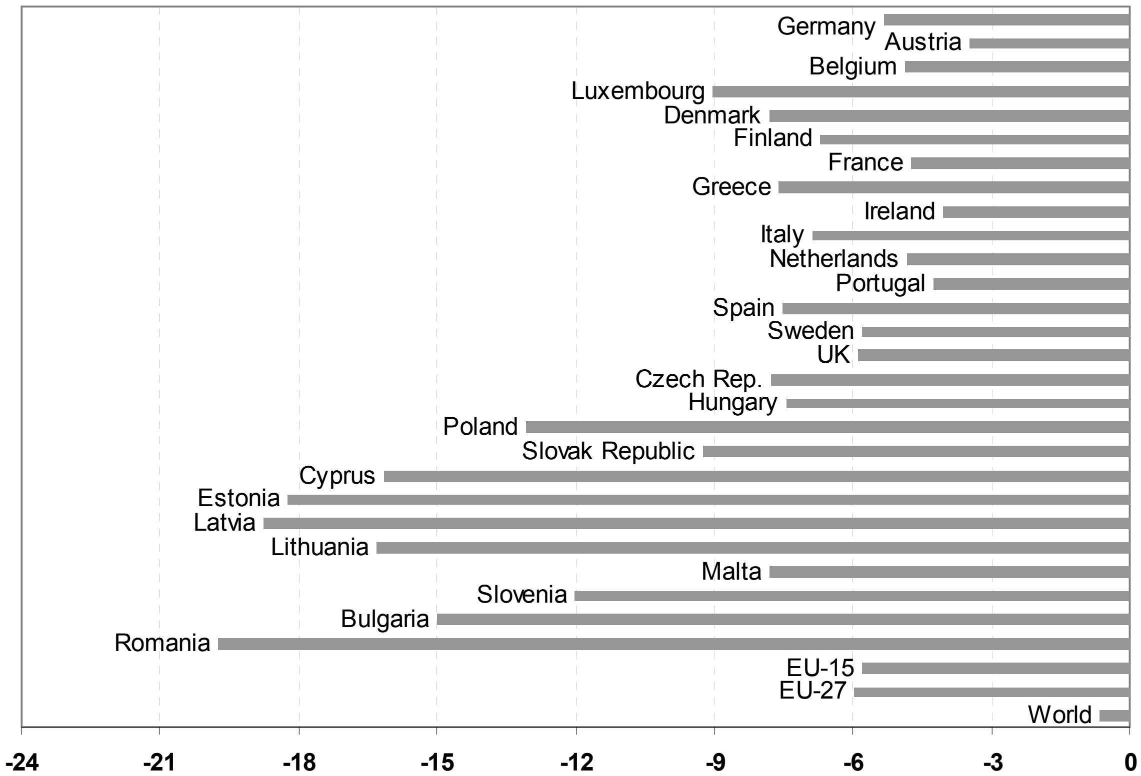


Figure 9: Total primary energy supply in Mtoe: percentage deviations of scenario S2H against baseline BH in 2020



The scenarios are not designed to necessarily meet the EU renewables target of a 20% renewables share in final energy consumption in 2020. The share will increase from around 10% today to above 14% even in the baseline with low energy prices as instruments such as feed in tariffs and biofuel quotas will continue. In scenario S1H the target will be missed with around 18% in 2020. Only in scenarios S2H, S2HE and S2HI, the target is met (almost 20%).

Energy-related carbon emissions are reduced in all EU countries against the baseline (Figure 8). The highest percentage reduction can be seen for many of the new member states with still high energy intensity and low energy prices. In these countries the relative price increase is higher than in countries like Germany or the UK with already high energy taxes and overall energy prices.

Additional ETS revenues, material tax revenues and carbon taxes revenues from the industry sector are recycled back to industry via reductions in employers' social security contributions (or wage subsidies in some countries). The revenues from the carbon tax on households (0.33% for Germany) are used for income tax reduction (Table 3). For EU-27 overall revenues from ETS and ETR reach about 2% of GDP in 2020. These numbers are already at the upper end of different calculations, as additional EU efforts for energy efficiency and renewable energy are not taken into account that will per se reduce the ETS price. The use of flexible mechanisms as CDM will further reduce the revenues and earmarking of part of the revenues for mitigation and adaptation measures in emerging and developing countries limits the recycling into labour costs.

The scenarios do not take the current economic crisis into account. According to the IEA (2009), the crisis will reduce carbon emissions also in the long run, which will lead to lower carbon prices and revenues to reach fixed targets (or make tighter targets less costly).

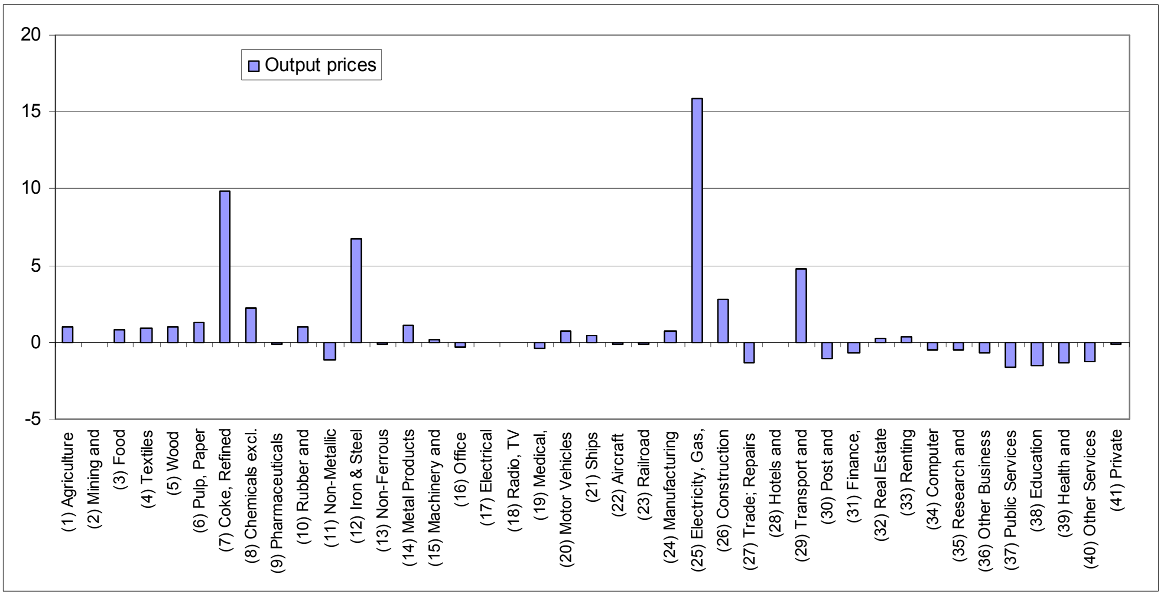
Table 3: Additional revenues in % of GDP in 2020

S2H	DE	UK	EU-27
ETS revenues	0,83	0,64	0,59
carbon tax (industry)	0,52	0,44	0,54
carbon tax (households)	0,33	0,41	0,36
material tax	0,41	0,29	0,56
Sum	2,09	1,78	2,05

The material or carbon taxes increase the prices of product groups according to their direct and indirect material and carbon content. The recycling mechanism reduces social security contributions and lowers labour costs again according to the direct and indirect labour content of sector output. The ETR reduces output prices in labour-intensive service sectors and increases prices in carbon- and material-intensive industry sectors.

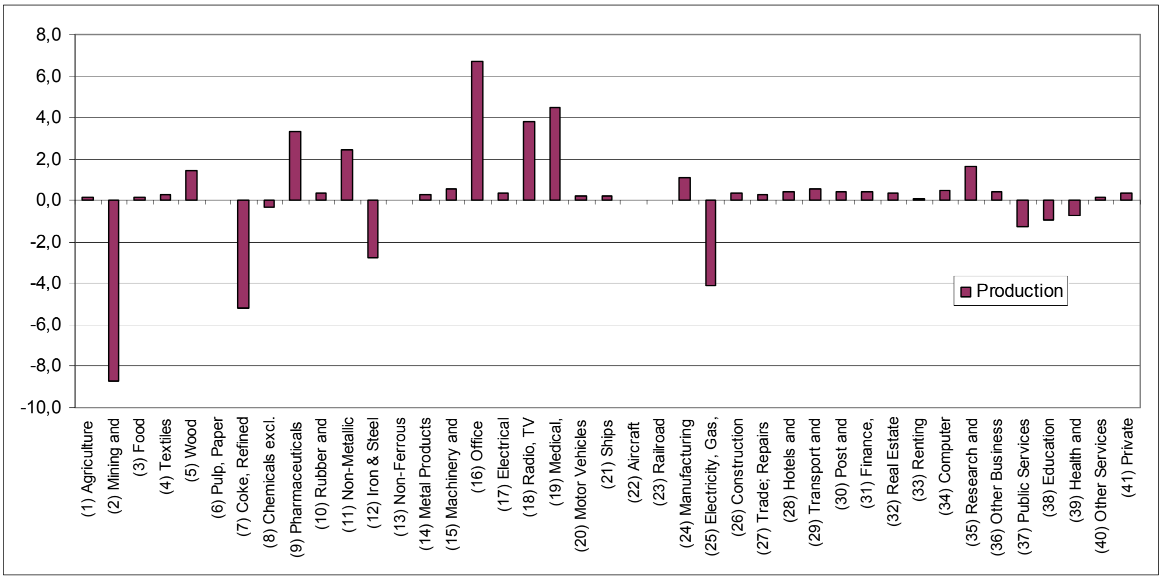
The example of Germany shows for the trade-intensive sectors machinery (15-17), motor vehicles (20) and other transport equipment (21-23) the effect being insignificant. Iron and steel (12) and chemicals without pharmaceuticals (8) face the highest price increases of trade-intensive sectors. As the German iron and steel industry is mainly delivering high quality steel to the German car industry and more and more to the German windmill industry, negative competitiveness impacts will be limited. Exchange rate variations against non-EU competitors have been much higher in the past.

Figure 10: Output price impacts of scenario S2H in Germany: deviations from baseline BH in 2020



The higher prices of the carbon- and material-intensive products will reduce price competitiveness on export markets and lead to some loss in the share of domestic markets to imports from other countries. This loss of price competitiveness, that has to be related to the assumptions about low market development of energy efficiency and RES technologies in other part of the world – i. e. it is partly by assumption -, will be offset by gains in the labour-intensive sectors, if real wage costs per unit of output have fallen in the ETR through recycling of revenues to reduce employers' social security contributions. Any improvement in non-price competitiveness will also raise exports. The extra employment will raise incomes, raising consumption and output. The overall impact on sector output depends on counterworking effects, which in sum are more negative for iron and steel and a few service sectors and positive for a few industry sectors. For most industries, the output effect is insignificant. The producers of fossil fuels have to reduce their production due to lower demand for their products, of course.

Figure 11: Output impacts of scenario S2H in Germany: deviations from baseline BH in 2020



Employment impacts are positive for most sectors as labour productivity decreases and wage rates fall in relation to the consumer prices (CPI) and the output prices (Table 4). The relative costs of labour are lower than in the baseline without the ETR reform. Only around a quarter of the employment increase takes place in industry.

Table 4: Employment impacts of scenario S2H in Germany – deviations from baseline BH in 2020

Employment in 2020	Deviation from BH	Deviation from BH
	in %	absolute
Agriculture, forestry	2.4	9.0
Industry	0.9	65.3
Non-metallic minerals	2.4	6.2
Iron and steel	-2.8	-3.7
Machinery and equipment	0.5	5.6
Electrical machinery	0.4	1.8
Construction	3.7	44.9
Trade and transport	1.0	82.9
Business services	1.7	76.7
Other services	-0.2	-21.6
Total	0.7	250.6

Concerning the wage rate, two countervailing effects have to be considered: When the labour market is characterised in terms of the "real wage bargaining" model, as in E3ME and GINFORS, with market power on both sides of the labour market, i.e. employers and trade unions, consumer price increases will lead to wage increases (the econometrically estimated factor is 0.85 for Germany). On the other hand, labour productivity is another important factor for the wage bargaining. The estimated elasticity for Germany is 0.63, i. e. a 1% increase of labour productivity leads to wage increases of 0.63%. Higher labour demand due to lower labour costs thus reduces the wage increase. In the end, the German economy is more labour-intensive than without the ETR, partly due to the structural change towards labour-intensive industries.

Additional exports in scenarios S2HE mainly create new jobs in machinery and in related business services (Table 5). A shift in the input structure of the utility sector leads to a shift in the industry structure and creates a few jobs in the service sector (Table 6).

Table 5: Employment impacts of scenario S2HE in Germany – deviations from scenario S2H in 2020

Employment in 2020	Deviation from S2H	Deviation from S2H
	in %	absolute
Agriculture, forestry	-0,1	-0,2
Industry	0,3	19,4
Non-metallic minerals	0,2	0,5
Iron and steel	0,4	0,5
Machinery and equipment	1,3	13,0
Electrical machinery	2,4	11,7
Construction	0,1	1,8
Trade and transport	0,0	2,6
Business services	0,7	30,8
Other services	0,1	10,7
Total	0,2	63,4

Table 6: Employment impacts of scenario S2HI in Germany – deviations from scenario S2H in 2020

Employment in 2020	Deviation from S2H	Deviation from S2H
	in %	absolute
Agriculture, forestry	-0,1	-0,2
Industry	0,0	0,0
Non-metallic minerals	2,5	6,5
Iron and steel	-2,7	-3,6
Machinery and equipment	0,8	7,8
Electrical machinery	0,4	1,9
Construction	0,0	-0,4
Trade and transport	0,0	0,7
Business services	0,2	11,5
Other services	0,0	5,6
Total	0,0	16,7

7 CONCLUSIONS

The GINFORS model has been applied to assess economic and environmental impacts of ETS and ETR to reach the EU GHG targets in the EU in 2020. Results show positive employment effects and only small negative impacts on GDP. Economic impacts depend on the level of international energy prices, the recycling mechanism, country specifics such as carbon and energy intensity and structure of energy consumption.

Although there is large evidence, that eco-innovation is positively driven by higher energy-prices, quantification is difficult. In two simulations possible impacts of a shift in the industry structure towards renewable energy in the electricity sector and an overall increase of EU exports due to higher global demand for renewable energy are modelled. The main results can be summarized as follows:

An environmental tax reform, shifting taxes from labour to energy and resources will create additional jobs and trigger eco-innovation. Impacts of eco-innovation in the form of additional EU exports or shifts in industry structures will slightly increase GDP and create a smaller number of additional jobs. These findings correspond to results from the EmployRES study. As ETR is directly targeting labour costs, it will create additional jobs in the short and medium term. The impacts of eco-innovation in the form of cost reduction and new technologies will play a larger role in the longer term.

ETR together with auctioning of ETS allowances can be a major source of revenues for EU countries in the future. But at least the share of revenues from carbon pricing will be limited. Part of the revenues will have to be earmarked for adaptation and mitigation measures in developing countries.

As each reform a major ETR in Europe will create winners and losers. On a sector level, carbon and material-intensive industries will have to face economic loss. On a country level, carbon-intensity but also the overall flexibility of economies is quite important. International cooperation will reduce economic pressure on countries and sectors, although structural change away from the carbon-intensive industries, together with technological change, is inherent to any successful climate mitigation policy.

ETR and ETS, if allowances are fully auctioned, are additional sources of public revenues. The discussion on grandfathering vs. auctioning of ETS allowances should be directed more towards this point. Countries, which give allowances away for free, will lack money to ease structural change and invest in low-carbon technologies.

Results should be carefully related to the EU policy debate. In the model simulations the single carbon price is the only instrument to reach the EU 2020 GHG targets. Renewable energy and efficiency policies will also contribute to carbon reduction and have to be taken into account, when comparing the results (especially the high carbon prices) to other studies. Both reduce the potential revenues from fossil energy carriers and carbon emissions. There are different renewable energy and efficiency policies that could further improve the economic impacts of reaching the climate and energy targets. The results clearly indicate to intensify the discussion on market-based instruments, but in the end a policy mix will be needed to reach the EU GHG targets.

References

Almon, C. (1991): The INFORUM Approach to Interindustry Modeling. Economic Systems Research, Vol. 3, pp. 1-7.

Amin, A. & Cohendet, P. (2004): The Architecture of Knowledge. Firms, Capabilities and Communities. Oxford University Press, Oxford.

Barker, T., Meyer, B., Pollitt, H. & Lutz, C. (2007a): Modelling Environmental Tax Reform in Germany and the United Kingdom with E3ME and GINFORS, Petre Working Paper, Cambridge and Osnabrueck. http://www.petre.org.uk/papers.htm

Barker, T., Junankar, S., Pollitt, H. & Summerton, P. (2007b): Carbon leakage from unilateral environmental tax reforms in Europe, 1995-2005. Energy Policy, Vol. 35, pp. 6281–6292.

Boira-Segarra, I. (Mott McDonald), et. al (2004): Renewable Supply Chain Gap Analysis. Study on behalf of the Department of Trade and Industry.

Brunnermeier, S. B. & Cohen, M. A. (2003): Determinants of environmental innovation in US manufacturing industries. Journal of Environmental Economics and Management, Vol. 45, pp. 278-293.

Buen, J. (2006): Danish and Norwegian wind industry: The relationship between policy instruments, innovation and diffusion. Energy Policy, Vol. 34 (18), pp. 3887-3897.

Carlsson, B. & Stankiewicz, R. (1991): On the nature, function and composition of technological systems. Journal of Evolutionary Economics, Vol. 1 (2), pp. 93-118.

Christiansen, A. C. & Skjaerseth, J. B. (2005): Climate change policies in Norway and the Netherlands: Different instruments, similar outcome? Energy & Environment, Vol. 16(1), pp.1-25.

Dosi, G. (1988): Sources, Procedures, and Microeconomic Effects of Innovation. Journal of Economic Literature, Vol. 26, pp. 1120-1171.

de Vries, F. & Medhi, N. (2008): Environmental regulation and international innovation in automotive emissions control technologies. Environmental Policy, Technological Innovation and Patents. Paris, Organisation for Economic Cooperation and Development.

DG TREN (2008): European Energy and Transport. Trends to 2030 - update 2007, Luxembourg.

Edler, J. (ed.) (2006): Nachfrageorientierte Innovationspolitik. Büro für Technikfolgenabschätzung beim Deutschen Bundestag (TAB), Arbeitsbericht Nr. 99, Berlin.

Edquist, C. (2001): The System of Innovation Approach and Innovation Policy: An account of the state of the art. Lead paper presented at the DRUID Conference, 12-15 June 2001, Aalborg. Online: http://www.druid.dk/conferences/nw/paper1/edquist.pdf (accessed: 06-02-2007).

Ekins, P. & Speck, S. (2010): Environmental Tax Reform (ETR): Resolving the conflict between economic growth and the environment. Oxford University Press.

EREC (2008): Energy [r]evolution, A sustainable global energy outlook. Greenpeace International, European Renewable Energy Council (EREC)

Fagerberg, J., Mowery, D. C. & Nelson, R. R. (eds.) (2005): The Oxford Handbook of Innovation. Oxford University Press, Oxford.

Fischer, C., Parry, I. W. H. & Pizer, W. A. (2003): Instrument choice for environmental protection when technological innovation is endogenous. Journal of Environmental Economics and Management, Vol. 45, pp 523-545.

Fraunhofer ISI, ECOFYS, Energy Economics Group, Rütter + Partner, SEURECO & LEI [ISI et al.] (2009): The economic impact of renewable energy policy on economic growth and employment in the European Union. Brussels.

Frondel, M., Horbach, J. & Rennings, K. (2008): What triggers environmental management and innovation? Empirical evidence for Germany. Ecological Economics, Vol. 66(1), pp. 153-160.

GHK, Cambridge Econometrics & IEEP (2007): Links between the environment, economy and jobs', Final Report submitted to DG Environment, European Commission, November 2007.

Giljum, S., Behrens, A., Hinterberger, F., Lutz, C. & Meyer, B. (2008): Modelling scenarios towards a sustainable use of natural resources in Europe. Environmental Science and Policy, Vol. 11, pp. 204-216.

Görlach, B., Knigge, M. & Lückge, H. (2005): Impacts of the Ecological Tax Reform on Innovation and Market Diffusion. Ecologic, Berlin [in German].

Green, M. A. (2000): Photovoltaics: technology overview. Energy Policy, Vol. 28 (14), pp. 989-998.

Grossmann, A., Lehr, U., Lutz, C. & Wolter, M.I. (2008): Gesamtwirtschaftliche Effekte der Umsetzung der EU Ziele im Bereich Erneuerbare Energien und Gebäudeeffizienz in Österreich bis 2020. Studie im Auftrag des Lebensministeriums, Wien 05/08.

Hage, J. & Hollingsworth, J. R. (2000): Idea Innovation Networks: A Strategy for Integrating Organizational and Institutional Analysis. Organization Studies, Vol. 21 (5), pp. 971-1004.

Hauschildt, J. (2004): Innovationsmanagement. Vahlen, München.

Hemmelskamp, J. (1997): Environmental policy instruments and their effects on innovation. European Planning Studies, Vol. 5 (2), pp. 177-195.

Hoglund Isaksson, L. (2005): Abatement costs in response to the Swedish charge on nitrogen oxide emissions. Journal of Environmental Economics and Management, Vol. 50, pp. 102-120.

Hullmann, A. (2001): Internationaler Wissenstransfer und technischer Wandel (Dissertation). Physica-Verlag, Heidelberg.

http://www.ecologic.de/download/projekte/1850-1899/1879/1879_5_innovation.pdf

http://www.olis.oecd.org/olis/2006doc.nsf/LinkTo/NT0000776E/$FILE/JT03221359.PDF

http://www.technopolis-group.com/resources/downloads/661_report_final.pdf http://www.umweltbundesamt.de/uba-info-presse-e/hintergrund/oekosteuer.pdf

International Energy Agency [IEA] (2008): World Energy Outlook 2008, Paris.

International Energy Agency [IEA] (2009): World Energy Outlook 2009, Paris.

Jacobsson, S., Andersson, B. A., & Bångens, L. (2002): Transforming the energy system - the evolution of the German technological system for solar cells. SPRU (Science and Technology Policy Research), University of Sussex: *Electronic Working Paper Series*, No. 84. Online: http://www.sussex.ac.uk/Units/spru/publications/imprint/sewps/sewp84/ sewp84.pdf (accessed: 05-14-2007).

Jaffe A, & Stavins R. (1995): Dynamic incentives of environmental regulations: the effects of alternative policy instruments on technology diffusion. Journal of Environmental Economics and Management, Vol. 29(3), pp. 43-63.

Jaffe A. B. & Palmer, K. (1997): Environmental regulation and innovation: a panel data study. The Review of Economics and Statistics, Vol. 79, pp. 610-619.

Jaffe, A. B., Newell, R. G. & Stavins, R. N. (2002): Environmental Policy and Technological Change. Environmental and Resource Economics, Vol. 22 (1-2), 2002, pp. 41-70.

Johnstone, N., Hascic, I. & Popp, D. (2009): "Renewable energy policies and technological innovation: evidence based on patent counts", Environmental & Resource Economics, published online 19 August 2009.

Johnstone, N. & Hascic, I. (2008): Renewable energy policies and technological innovation: energy source and instrument choice. Environmental Policy, Technological Innovation and Patents. Paris, Organisation for Economic Cooperation and Development.

Johnstone, N. (2005): The Innovation Effects of Environmental Policy Instruments. In: Horbach. J. (ed): Indicator Systems for Sustainable Innovation, Physica-Verlag HD.

Johnstone, N., Hascic, I. & Ostertag, K. (2008): Environmental policy, technological innovation and patent activity. Environmental Policy, Technological Innovation and Patents. Paris, Organisation for Economic Cooperation and Development.

Jung C., Krutilla K., & Boyd R. (1996): Incentives for advanced pollution abatement technology at the industry level: an evaluation of policy alternatives. Journal of Environmental Economics and Management, Vol. 30(1), pp 95-111.

Kammen, D. M., Kapidia, K. & Fripp, M. (2004): Putting Renewables to Work: How Many Jobs Can the Clean Energy Industry Generate? University of California, Berkeley.

Kemp, R. (1997): Environmental policy and technical change – a comparison of the technological impact of policy instruments, Cheltenham, Edward Elgar.

Kemp, R. (1998): The diffusion of biological waste-water treatment plants in the Dutch food and beverage industry. Environmental and Resource Economics, Vol. 12, pp. 113-136.

Kemp, R. (2000): Technology and environmental policy – innovation effects of past policies and suggestions for improvement. In: OECD proceedings – innovation and the environment, Paris, Organisation for Economic Cooperation and Development.

Kerr, S. & Newell R. G. (2003): Policy-induced technology adoption: evidence from the US lead phasedown. Journal of Industrial Economics, Vol. 51, pp. 317-343.

Klaassen, G., Miketa, A., Larsen, K. & Sundqvist, T. (2005): The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics, Vol. 54, pp. 227-240.

Kline, S. & Rosenberg, N. (1986): An overview of innovation. In: Landau, R. (ed.): The positive sum strategy: Harnessing technology for economic growth, pp. 275-306.

Knigge, M. & Görlach, B. (2005): Effects of Germany's Ecological Tax Reforms on the Environment, Employment and Technological Innovation, Ecologic, Berlin.

Langniss, O. (2003): Governance Structures for Promoting Renewable Energy Sources. Dissertation. Lund, Stuttgart

Lanjouw, J. O. & Mody, A. (1996): Innovation and the international diffusion of environmentally responsive technology. Research Policy, Vol. 25, pp. 549-571.

Lehr, U., Nitsch, J., Kratzat, M., Lutz, C. & Edler, D. (2008): Renewable Energy and Employment in Germany. Energy Policy, Vol. 36, pp. 108-117, DOI:10.1016/j.enpol.2007.09.004.

Lehr, U., Wolter, M.I. & Großmann, A. (2009): Economic Impacts of RES Obligations in Austria – an Application of the Macro-Econometric Model e3.at. GWS Discussion Paper 2009/1, Osnabrück.

Lundvall, B.-A., Johnson, B., Andersen, E. S., & Dalum, B. (2001): National systems of production, innovation and competence building. Research Policy, Vol. 31, pp. 213-231.

Lutz, C. & Giljum, S. (2009): Global resource use in a business as usual world until 2030. Updated results from the GINFORS model. In: Bleischwitz, R., Welfens, P.,& Zhang, Z. (Eds.): Sustainable Growth and Resource Productivity – Economic and Global Policy Issues. Greenleaf Publishers, pp. 30-41.

Lutz, C. & Meyer, B. (2008): Beschäftigungseffekte des Klimaschutzes in Deutschland. Untersuchungen zu gesamtwirtschaftlichen Auswirkungen ausgewählter Maßnahmen des Energie- und Klimapakets. Forschungsbericht 205 46 434, Dessau-Roßlau.

Lutz, C. & Meyer, B. (2009a): Environmental and Economic Effects of Post-Kyoto Carbon Regimes. Results of Simulations with the Global Model GINFORS. Energy Policy, Vol. 37, pp. 1758-1766.

Lutz, C. & Meyer, B. (2009b): Economic impacts of higher oil and gas prices. The role of international trade for Germany. Energy Economics, 31, pp. 882-887.

Lutz, C., Meyer, B., Nathani, C. & Schleich, J. (2005): Endogenous technological change and emissions: The case of the German steel industry. Energy Policy 33 (9), pp. 1143-1154.

Lutz, C., Meyer, B. & Wolter, M. I. (2010): The Global Multisector/Multicountry 3-E Model GINFORS. A Description of the Model and a Baseline Forecast for Global Energy Demand and CO_2 Emissions. Journal of Sustainable Development, special issue on global models, forthcoming.

Malerba, F. & Orsenigo, L. (1997): Technological Regimes and Sectoral Patterns of Innovative Activities. In: Industrial and Corporate Change, Vol. 6 (1), pp. 83-117.

Malerba, F. (1992): Learning by Firms and Incremental Technical Change. The Economic Journal, Vol. 102 (413), pp. 845-859.

Malerba, F. (2005): Industrial dynamics and innovation: progress and challenges. Presidential Address delivered at the 32nd Conference of the European Association for Research in Industrial Economics (EARIE), 1-4 September 2005, Porto.

Malerba, F. (2006): Innovation and the evolution of industries. Journal of Evolutionary Economics, Vol. 16, pp. 3-23.

McGinty, M. & de Vries, F. P. (2009): Technology diffusion, product differentiation and environmental subsidies. The B.E. Journal of Economic Analysis and Policy, Vol. 9(1).

Meyer, B & Lutz, C. (2007): The GINFORS model. Model Overview and Evaluation. Petre Working Paper, Osnabrueck. http://www.petre.org.uk/papers.htm

Meyer, B., Lutz, C., Schnur, P. & Zika, G., (2007): Economic Policy Simulations with Global Interdependencies: A Sensitivity Analysis for Germany. Economic Systems Research, Vol. 19, pp. 37-55.

Mickwitz, P., Hyvättinen, H. & Kivimaa, P. (2008): The role of policy instruments in the innovation and diffusion of environmentally friendlier technologies: popular claims versus case study experiences. Journal of Cleaner Production, Vol. 16(1S1), 162-170.

Miketa, A. & Schrattenholzer, L. (2004): Experiments with a methodology to model the role of R&D expenditures in energy technology learning processes; first results. Energy Policy, Vol. 32 (15), pp. 1679-1692.

Milliman, S. R. & Prince, R. (1989): Firm incentives to promote technological change in pollution control. Journal of Environmental Economics and Management, Vol. 17, pp. 247-265.

Millock, K. & Nauges, C. (2006): Ex post evaluation of an earmarked tax on air pollution. Land Economics, Vol. 82(1), pp. 68-84.

Montero, J-P. (2002): Market structure and environmental innovation. Journal of Applied Economics, Vol. 2, pp. 293-325.

Moreno, B. & López, A. J. (2007): The effect of renewable energy on employment. The case of Asturias (Spain). Renewable and Sustainable Energy Rewiews (2007), doi: 10.1016/j.rser.2006.10.011.

Mowery, D. & Rosenberg, N. (1979): The influence of market demand upon innovation: A critical review of some recent empirical studies. Research Policy, Vol. 8, pp. 102-153.

Newell, R. G., Jaffe, A. B. & Stavins, R. N. (1999): The induced innovation hypothesis and energy-saving technological change. Quarterly Journal of Economics, Vol. 114, pp 941-975.

Norberg-Bohm V. (1999): Stimulating 'green' technological innovation: An analysis of alternative policy mechanisms. Policy Sciences, Vol. 32(1), pp. 13-38.

OECD (2009): Sustainable Manufacturing and Eco-innovation: Towards a Green Economy. OECD Policy Brief, June 2009.

Pavitt, K. (1984): Sectoral patterns of technological change: Towards a taxonomy and a theory. Research Policy, Vol. 13, pp. 343-373.

Popp, D. (2002): Induced innovation and energy prices. The American Economic Review, Vol. 92(1), pp. 160-180.

Popp, D. (2005): Lessons from patents: Using patents to measure technological change in environmental models. Ecological Economics, Vol. 54, pp. 209-226.

Porter, M. & van der Linde, C. (1995): Toward a new conception of the environment competitiveness relationship. Journal of Economic Perspectives, Vol. 9(4), pp. 97-118.

Rammert, W. (2002): The Cultural Shaping of Technologies and the Politics of Technodiversity. In: Sorensen, K.; Williams, R. (eds.): Shaping technology, Guiding Policy: Concepts, Spaces and Tools. Elgar, Cheltenham, pp. 155-172.

Requate, T. (2005): Dynamic incentives by environmental policy instruments – a survey. Ecological Economics, Vol. 54, pp. 175-195.

Roloff, N., Lehr, U., Krewitt, W., Fuchs, G., Wassermann, S., Weimer-Jehle, W. & Schmidt, B. (2008): Success determinants for technological innovations in the energy sector - the case of photovoltaics. In: Möst, D., Fichtner, W., Ragwitz, M. & Veit, D. (eds.): New methods for energy market modelling. Proceedings of the First European Workshop on Energy Market Modelling using Agent-Based Computational Economics. Universitätsverlag Karlsruhe.

Rothwell, R. (1995): The fifth generation innovation process. In: Oppenländer, K.H., Popp, W. (eds.): Innovationen und wirtschaftlicher Fortschritt: betriebs- und volkswirtschaftliche Perspektiven. Bern, pp. 9-26.

Schumpeter, J. (1942): Capitalism, Socialism and Democracy, New York, Harper.

Skjærseth, J. B. & Christiansen, A. C. (2005): Environmental policy instruments and technological change in the energy sector: findings from comparative empirical research. Energy & Environment, Vol. 17 (2), pp. 223-241.

Snyder, L. D., Miller, N. H. & Stavins, R. N. (2003): The effects of environmental regulations on pollution emissions: evidence from plant-level data. American Economic Review, Vol. 93(2), pp. 431-435.

Technopolis (2008): Eco-innovation: Final Report for Sectoral Innovation Watch, May 2008.

Volleburgh, H. (2007): Impacts of environmental policy instruments on technological change. Report for Joint Meetings of Tax and Environment Experts, OECD Environment Directorate, February 2007 (com/env/epoc/ctpa/cfa(2006)36/final)

Zimmermann, H., Wohltmann, M. & Hansjürgens, B. (1996): Umweltabgaben und Innovation, Analytica, Marburg.

Annex 1: Classification of refereed journal articles

Reference	Type					Instrument						Area					Stage		Relevance
	Theoretical	Empirical	Case study	Review	Qualitative	Taxes	Permits	Subsidies	Voluntary	Command	Regulation	Energy	Air	Water	Other	General	Innovation	Diffusion	
Brunnermeier & Cohen (2003)		X									X					X	X		**
Buen (2006)					X			X	X			X					X	X	*
Christiansen & Skjaerseth (2005)			X			X			X			X					X	X	***
Fischer et al (2003	X					X	X									X	X	X	***
Frondel et al (2008)		X				X	X	X	X	X						X	(X)	(X)	***
Hemmelskamp (1997)				X		X	X	X		X				X	X		(X)		**
Hoglund Isaksson (2005)		X				X							X				(X)	(X)	***
Jaffe & Stavins (1995)	X	X				X[1]		X		X		X						X	***
Jaffe & Palmer (1997)		X									X					X	X		**
Jaffe et al (2002)				X	X	X	X	X		X		X	X				X	X	***
Jung et al (1996)	X					X	X	X		X						X	(X)	(X)	**
Kemp (1998)		X				X								X				X	***
Kerr & Newell (2003)		X					X			X			X					X	*
Klaassen et al (2005)		X						X				X					X	X	**
Lanjouw & Mody (1996)		X									X	X	X	X			X	X	**
McGinty & de Vries (2009)	X							X								X		X	**
Mickwitz et al (2008)			X			X		X		X		X	X	X			X	X	***
Milliman & Prince (1989)	X					X	X			X						X	X	X	***
Millock & Nauges (2006)	X	X				X		X					X					X	***
Montero (2002)	X					X	X			X							X		***
Newell et al (1999)		X				X[1]				X		X					X		***
Norberg-Bohm (1999)					X	X	X		X	X					X		X		**
Popp (2002)		X				X[1]						X					X		***
Popp (2005)				X			X			X						X	X	X	**
Porter & van der Linde (1995)					X	X	X			X						X	X		**
Requate (2005)				X		X	X			X						X	X	X	***
Skjærseth & Christiansen (2005)			X			X		X	X	X		X	X				X	X	***
Snyder et al (2003)		X								X			X	X				X	*

[1] Study considers impact of factor prices on innovation

Annex 2: Classification of books and book chapters

Reference	Type					Instrument						Area					Stage		Relevance
	Theoretical	Empirical	Case study	Review	Qualitative	Taxes	Permits	Subsidies	Voluntary	Command	Regulation	Energy	Air	Water	Other	General	Innovation	Diffusion	
Johnstone (2005)					X	X	X			X			X				X	X	***
Johnstone & Hascic (2008)		X				X	X	X	X	X		X					X		***
Kemp (1997)	X	X		X		X	X	X	X	X		X	X	X			X	X	***
Kemp (2000)				X		X	X	X	X	X						X	X	X	**
de Vries & Medhi (2008)		X				X[1]				X			X				X		***

[1] Study considers impact of factor prices on innovation

Annex 3: Classification of reports

Reference	Type					Instrument						Area					Stage		Relevance
	Theoretical	Empirical	Case study	Review	Qualitative	Taxes	Permits	Subsidies	Voluntary	Command	Regulation	Energy	Air	Water	Other	General	Innovation	Diffusion	
Görlach et al (2005)			X			X		X				X					X	X	***
Knigge & Görlach (2005)			X			X		X				X					X	X	***
Technopolis (2008)				X	X			X		X						X	X		*
Volleburgh (2007)				X		X		X	X	X		X	X	X	X		X	X	***