A note on the induced effects of carbon prices and R&D subsidies in carbon-free technologies[1]

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Abstract

This note focuses on two types of distortions that can prevent the market from functioning optimally. The first results from CO_2 emissions generated by the consumption of fossil fuels. The second is related to R&D activities, since innovators are generally incapable of securing the totality of the benefits created by their innovations. Two types of instruments can be used in order to correct for these externalities: a carbon price on the one hand, and research subsidies on the other hand. These instruments tend to interact in a complex manner when the economy is in equilibrium. The paper first recalls the basic economic principles which govern the correction of environmental and research externalities and describes four endogenous growth models that provide information about the interaction between related public policies. Although they differ in the ways how innovation, production, the climate and damages have been taken into account, all of them reach the following consensual result: the beneficial effect of the carbon price is reinforced by the simultaneous implementation of R&D subsidies in favour of carbon-free energies and vice-versa. Furthermore, early action is necessary in order to reduce the social costs of climate change mitigation.

Keywords

carbon tax, carbon trading, climate change, endogenous growth models, environmental externality, public policies, R&D subsidies, research externality

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1 Introduction

Climate change – a consequence of releasing excess greenhouse gas emissions into the atmosphere – is likely to seriously disrupt the world economy in the decades to come. In his widespread and highly debated report published in 2007, the economist N. Stern estimated that the annual costs and risks of climate change would amount to 5% of the gross world product (GWP) now and forever, if the international community would not make any concerted effort to turn the situation around (Stern (2007)).

From a strictly economic point of view, greenhouse gas emissions can be compared to a negative environmental externality that needs to be internalised by means of a specific instrument. The carbon tax is one economic tool that is often considered to control for CO_2 emissions.[5] By increasing the price of fossil fuels, this tax leads to a reduction of their use and encourages the shift to carbon-free substitutes. Nonetheless, the deployment of renewable energies or abatement technologies requires considerable investments. For this reason, the transition falls within the scope of a mid- to long-term perspective during which technical progress plays an important role, since it improves the cost-effectiveness of carbon-free technologies.

According to the Porter Hypothesis (Ambec and Barla (2006)), a carbon price should incite firms to innovate[6]. Yet, the consideration of technical progress resulting from research also implies the emergence of a second type of distortion in the economy: externalities related to R&D activities such as the transmission of knowledge beyond the originator of the innovation (research spillovers). These externalities generally prevent innovators from securing all the rents associated with their innovation, which explains the existence of under-investment in R&D. According to different empirical studies, such investments have been found to be significantly lower than what would be optimal for society (Mansfield (1977), Pakes (1985), Jaffe (1986), Griliches (1992), Nadiri (1993), Jones and Williams (1998)).

[5] As CO_2 represents more than 70% of greenhouse gas emissions of an anthropic origin, we have decided to only take this source of emission into account.

[6] This theory, put forward by M. Porter, has become very popular in political debates, especially in the United States since it refutes the idea according to which environmental protection is only possible to the detriment to economic growth.

It would therefore be advisable to correct for this second type of externality as well, e.g. through R&D subsidies. However, by reducing the cost of using alternative energies, such subsidies are also likely to have an impact on the consumption of fossil fuels and thus on carbon emissions.

Associating these two externality sources – climate change and R&D – presupposes the emergence of undoubtedly complex interactions. As a result, economists are challenged with the task to develop models that are able to identify the optimal deployment of carbon prices and R&D subsidies and to explain their potential interactions.

A considerable amount of work has already been dedicated to environmental technical change and different reviews like Köhler et al. (2006), Gillingham et al. (2008), Popp et al. (2010), Heutel and Fischer (2013) or Löschel and Schymura (2013) survey both microeconomic and macroeconomic approaches in this area.

This note does not have the intention to provide another global review, but wants rather to focus explicitly on the interaction between environmental and innovation instruments. For this purpose, the basic economic principles governing the correction of the two externalities are briefly recalled in Section 2, before a selection of four different approaches analysing the interactions of the policy instruments is presented in Section 3. We discuss successively the models by Otto and Reilly (2008), Bosetti et al. (2011), Grimaud et al. (2011), and Acemoglu et al. (2012). All these contributions are top-down endogenous economic growth models with dedicated sectors of innovation for different technologies.[7]

Although all these models take into account endogenous technical change, the representation of the sectors, the way how innovation is integrated and how climate feedbacks or damage functions are modelled differ significantly from one approach to

[7] In practice, the two basic approaches to examine the links between the energy choices, the climate and the economic system are the top-down and bottom-up ones. As compared with bottom-up models, the top-down approach introduces a smaller level of decentralization, in particular for the energy markets. However, they can provide a general equilibrium analysis for different energy options in which both the climatic feedbacks on growth and the macro-economic feedbacks on climate are taken into account.
Technical progress in an endogenous growth model is integrated in such a way that decisions to finance R&D – which improve the productivity of one or several production factors – result in optimal behaviour.

another. For example, while Otto and Reilly (2008) describe an economy with seven different sectors in a computable general equilibrium framework, Bosetti et al. (2011) prefer to use an integrated assessment model with twelve different regions. Similar to the first two models, Grimaud et al. (2011) account for innovation through knowledge accumulation, whereas Acemoglu et al. (2012) directly improve the quality of intermediate goods.

In Section 4 we conclude by observing that despite of these methodological differences, the authors come to the same conclusion when it comes to the optimal policy-mix. It is always better to use both instruments, a carbon price together with a research subsidy in order to correct for externalities resulting from pollution and R&D. Furthermore, as far as the timing of policy intervention is concerned, early action is needed to reduce the social costs of climate change mitigation.

2 Correcting Externalities

2.1 Environmental Externalities

The British economist A. Pigou was the first to recommend the application of a corrective tax on externalities in 1920. The Pigovian tax is designed to internalise the marginal social cost generated by an economic activity, i.e. to take into account negative externalities affecting the market. Applied to polluting emissions, this tax enters the polluter's optimisation programme in order to modify its behaviour and to generate income intended to remedy the negative effects of said pollution[8]. In terms of greenhouse gas emissions, the carbon tax is a typical example of a Pigovian tax. Faced with the price signal implied by this tax, agents react by modifying their emitted quantities of carbon dioxide. An alternative would be to define the quantities and leave it up to the market to fix the prices. This approach can be realised through the deployment of an emission permit market such as the European Union Emissions Trading Scheme (EU-ETS). Without any other form of externality, these two approaches result in the same optimal emission level.

[8] The redeployment effects of the product of the tax are nonetheless highly dependent on economic and tax policies put in place by the state administrations.

The principle behind the carbon tax is based on attributing at each point in time the discounted flow of marginal damage provoked by the emission of an additional unit of carbon. The problem is fundamentally a dynamic one, since it is not the emissions themselves that constitute the source of the externality, but rather their accumulation in the atmosphere. Hence, the rate at which the tax changes matters just as much as its initial level. Three fundamental components govern this change over time:

- The rate at which the unit of carbon emitted into the atmosphere is absorbed by the natural environment (oceans, forests, biosphere, etc.). [9]
- The damage function which translates the change in the atmospheric carbon stock or in the average temperature (which is practically equivalent) into a monetary unit or a loss in social welfare. The main difficulty lies in defining such a function and incorporating the uncertainties on its characteristics.
- The rate at which the future damage flow is discounted, which is used to weight the damage according to its deferral over time.

The last two points have been the subject of intense debates for the last ten years within the economic community, a debate which has become polarised by the opposing opinions of Stern and Nordhaus. Stern (2007) defines a sophisticated climate damage function and uses a discount rate of 1.4%, which is considered to be extremely low by his opponents. Without any government intervention, such a rate would lead to a carbon tax of $85 per tonne of carbon dioxide. According to Stern, climate change could result in an annual loss of at least 5% of GWP[10], whereas the annual costs of stabilising the concentration at 500-550 ppm CO_2 equivalent would amount to about 1% of GWP by 2050 (ranging between -2% to +5% on each side). Nordhaus (2008) bases his work on an economic climate model as well, but chooses to apply a higher discount rate (5%), shrinking the annual cost of climate change to 3% of GWP and a current value of $8 per tonne of CO_2 - figures significantly lower than the estimates provided by Stern. However, the Nordhaus approach is not free from criticism

[9] Most theoretical economic studies apply a constant rate of decay and only integrated assessment models can be used to take into account the necessarily more complex reality of this self-regeneration process.
[10] If we consider a broader range of risks and consequences, the annual damage estimates would rise to 20% of the GWP or higher.

either, since the applied damage function is considered to be overly optimistic, attenuating the impact of the most severe damages.

Lastly, it should be pointed out that neither Stern nor Nordhaus integrate technical process in an endogenous manner. Stern, for instance, only stipulates that the faster innovations in the field of energy efficiency and carbon-sober technologies penetrate the market, the lower the cost of reducing greenhouse gas emissions will be.

2.2 Externalities Related to R&D

R&D activities generally involve several sources of externalities. Jones and Williams (2000) have identified four:

- Effect of duplication: Similar research projects are needlessly conducted at the same time by different teams;
- Intertemporal effect of research spillovers: Researchers do not necessarily consider the fact that their ideas or inventions will be used in the future to produce new ideas or inventions (standing on the shoulders of giants);
- Surplus appropriability effect: Inventors can only appropriate a part of the social value generated by their invention;
- Creative destruction process: Business sectors disappear when they become obsolete at the arrival of innovations (cf. Schumpeter).

The overall effect resulting from these distortions explains why the social value of an innovation generally differs from its private value. However, there is no theoretical consensus which identifies whether the private or social value predominates. While – for instance – the private value is lower than the social value in Romer's model (1990), Benassy (1998) shows that a slight change in the model can produce the reverse. The social value in the model by Aghion and Howitt (1992) can be either higher or lower, depending on the value of the parameters. Nevertheless, most empirical studies clearly demonstrate the dominance of the social value over the private value. The latter is two times lower than the social value according to Mansfield et al. (1977). Jones and Williams (1998 and 2000) estimate that in most cases research investments are four times less than what would be socially optimal, resulting in a difference of the same amplitude between the private and the social value of innovations.

From a theoretical viewpoint, several processes can be used to internalise research-related externalities. A first approach assumes that innovations are integrated into intermediate goods, protected by a system of patents and produced by monopolies (Aghion and Howitt (1992), Gerlagh et al. (2009)). In this case companies finance their R&D activities directly through the returns of their intermediate goods sales. Another approach would involve reducing the difference between the social value and the private value of innovations by subsidising them directly. These subsidies can, for instance, be derived from public policies supporting research. It is this form of economic regulation that we will focus on in this note.

3 Macroeconomic Endogenous Growth Models with Climate Change Mitigation Policies

3.1 Model by Otto and Reilly

Otto and Reilly (2008) analyse the interactions of a CO_2-trading scheme with diverse technology policies and study the cost-effectiveness of different policy combinations. They use a dynamic computable general equilibrium (CGE) model that takes into account the links between energy related CO_2 emissions, directed technical change and the economy.

For this purpose they define seven aggregate sectors where one representative producer interacts with one representative consumer in each sector. The sectors comprise (1) agriculture, (2) energy-intensive industries, (3) non-energy-intensive industries and services, (4) trade and transport, (5) energy, (6) CO_2-intensive electricity and (7) non-CO_2-intensive electricity. The energy sector consists of oil and gas industries and electricity is generated from (6) and (7). The final goods in each sector are produced by sector specific knowledge capital, physical capital, labour, energy inputs and intermediate inputs as depicted in Figure 1:

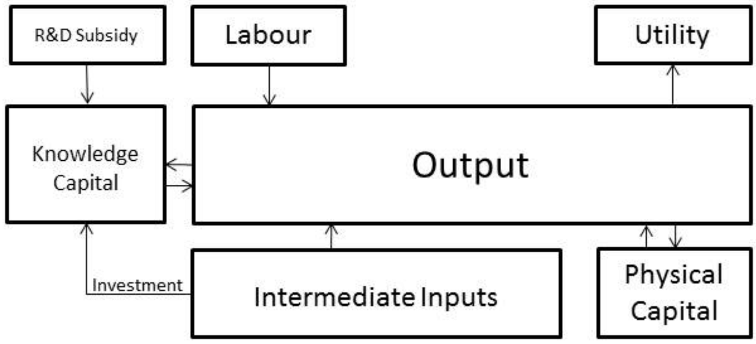

Figure 1: Final Good Production in a Representative Sector in the Otto and Reilly model

The representative consumer maximizes her welfare subject to an intertemporal budget constraint. Welfare is modelled as the discounted sum of consumption over time. Since the focus of this study lies on the cost-effectiveness of abatement options, the externality is captured by the production side and does not enter the utility function directly, like it is later the case in Acemoglu et al. (2012).

Producers can choose between several CO_2 abatement options including a reduction of total energy use, moving away from fossil fuels, enhancing production efficiency through technical change or to develop carbon capture and sequestration (CCS), which can be used with gas or coal production. Technical change can be induced by investing into sector specific knowledge capital and directed by investing relatively more in a certain sector.

The representative producer does not take into account intertemporal externalities coming from sector-specific knowledge spillovers and therefore underinvests in knowledge capital from a social welfare point of view. This externality can be corrected through an R&D subsidy. Figure 2 shows the relations between the respective energy inputs and the different sectors.

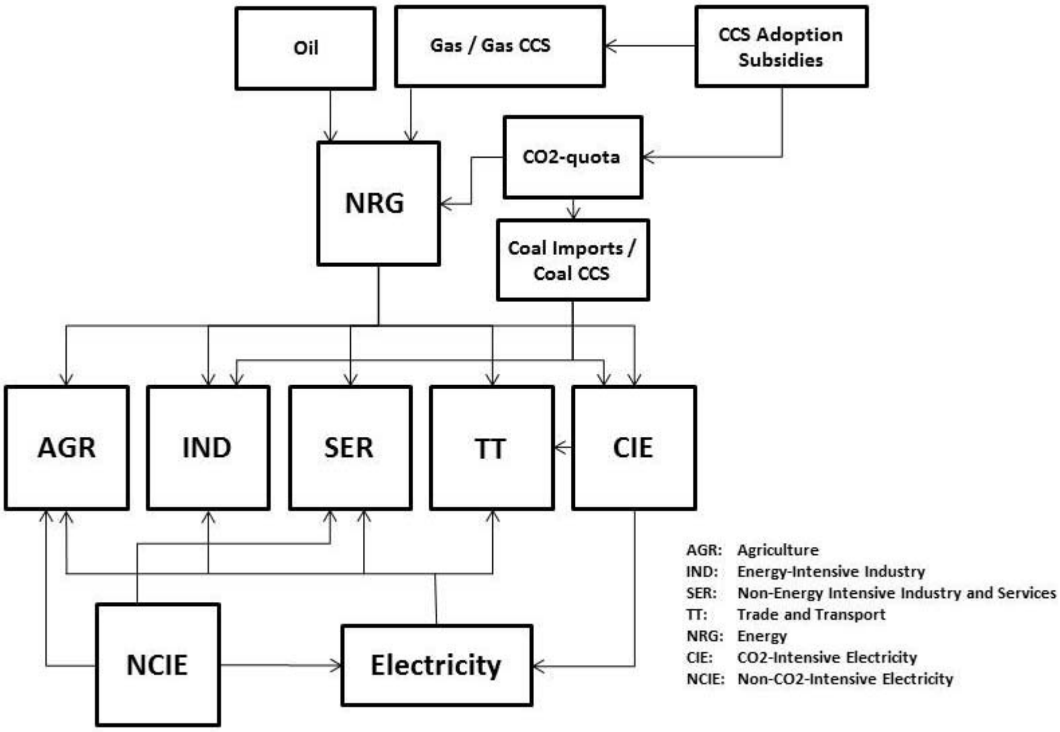

Figure 2 – Links between Energy Inputs and the Aggregate Sectors in the Otto and Reilly model

Otto and Reilly calibrate their model to the Dutch economy in 1999 and consider a 42-year time horizon. In addition to specific hypotheses on their parameters and elasticities they assume a balanced growth of 1.5% and an interest rate of 5%.

The authors compare the cost-effectiveness of a stand-alone environmental policy against the combination of environmental and technology policies. CO_2-intensive sectors are differentiated from non-CO_2-intensive sectors. The former are subject to a CO_2-trading scheme and CCS technology policies are either implemented through direct technology adoption subsidies (Figure 2) or through R&D subsidies in knowledge capital (Figure 1).

All in all they run four simulations. In the *first simulation* they use differentiated stand-alone CO_2-trading schemes and calculate a discounted welfare loss of 1.3%. The shadow price per ton of CO_2 is priced at €10 in the CO_2-intensive sectors and €0.10 in the non-CO_2-intensive sectors, inducing the adoption of the CCS technology from 2027. Under this scenario there is no need for a technology policy, since abatement targets are enough to trigger the adoption of the CCS technology.

In the *second simulation* differentiated CO_2-trading schemes are combined with an adoption subsidy. The welfare loss related to the policy-mix decreases to 0.84% and the shadow prices are €5.80 and €3 per ton of CO2 in the CO_2-intensive and the non-CO_2-intensive sectors, respectively. The adoption subsidy is around 20% and the CCS technology is immediately implemented as soon as the adoption subsidy is introduced. Since the subsidy corrects for the positive externality, the welfare loss is lower as compared to the first scenario.

In the *third simulation* differentiated CO_2-trading schemes are combined with a directed R&D subsidy leading to a discounted welfare loss of 1.23%. The shadow prices in the CO_2-intensive and in the non-CO_2-intensive sector are €9.75 and €1.05, respectively. The R&D subsidy increases to 59%. The authors find that CCS is adopted later and at a slower rate than under the second scenario, because R&D subsidies do not improve CCS competitiveness directly. Instead, sufficient knowledge capital has to be accumulated in order to decrease the input costs of knowledge capital, a process that takes more time. From a social-welfare perspective it is thus cheaper to use an adoption subsidy in order to internalise the technology externality.

The *fourth simulation* combines the differentiated CO_2-trading schemes and differentiated R&D subsidies, internalising technology externalities throughout the whole economy. From a welfare perspective this policy combination is superior to the previous ones, since the discounted welfare increases by 25.85% and more and faster adoption to CCS is realised as compared to the third simulation. However, this scenario comes with a per ton shadow price of €22.90 for the CO_2-intensive sector, €15.65 for the non-CO_2-intensive sector and very high R&D subsidies reaching 75% and 73%, respectively. From a fiscal perspective it is no longer possible to finance the subsidies with the revenues coming from the trading scheme, since the latter are seven times lower.

The main message of this paper is that a CO_2-trading scheme alone can be sufficient to induce adoption of the CCS technology under current abatement targets. However, adding optimally differentiated R&D subsidies in order to control for technology externalities can lead to faster adoption of the CCS technology and result in a more cost-effective way to reach the abatement target.

3.2 Model by Bosetti et al.

Bosetti et al. (2011) explore if stand-alone innovation policies can effectively stabilise the global climate. Furthermore, they investigate how innovation policies interact in combination with environmental policies such as carbon taxes or emission trading schemes. The authors use the integrated assessment WITCH[11] model (Bosetti et al. (2006)), an energy-economy-climate model which divides the world into twelve macro-regions. In these regions, final goods are produced by capital, labour and energy services. The main features of the WITCH model are the explicit integration of endogenous technical change in the energy sector and strategic interactions between the different regions. An illustration of the model for a representative region is shown in Figure 3.

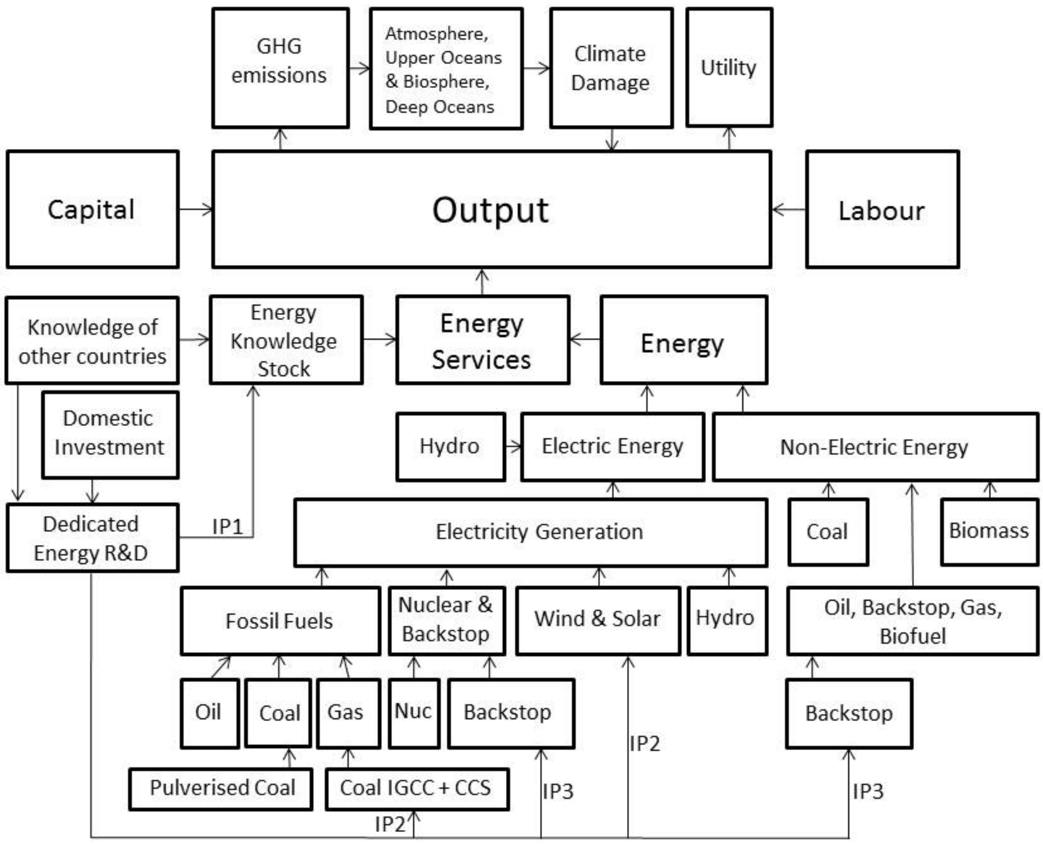

Figure 3 – Simplified Illustration of the WITCH Model for one representative Region

[11] World Induced Technical Change Hybrid (for more information see www.witchmodel.org)

Out of the four models under consideration, the WITCH model has the most sophisticated climate sector including a representation of the atmosphere, upper oceans and the biosphere and deep oceans. GHGs accumulate in the atmosphere and affect the global average temperature through radiative forcing. This increase is fed back into the economy via a damage function, negatively impacting output.

As far as technical change is concerned, R&D investments can be directed to three different innovation policies:

IP1 - energy efficiency enhancement,

IP2 - productivity improvement of wind, solar and CCS

IP3 - investment into advanced, breakthrough technologies

Energy efficiency is considered to be a substitute for physical energy. IP1 increases a region's energy efficiency capital stock, whereas IP2 improves the productivity of wind, solar or CCS through a reduction of investment costs, driven by the accumulation of knowledge capital. The latter mechanism holds also for IP3.

Since investment decisions in one region depend on investment decisions of other regions, innovation policies go along with international knowledge spillovers.

Environmental pollution and international knowledge spillovers have a public good character and incentives to free-ride are modelled through the game-theoretic feature of the WITCH model. It provides both, a globally optimal solution where full cooperation between the regions is achieved and all externalities can be internalised, as well as a non-cooperative Nash outcome where regions play a best response to other regions' choices.

Analysing the climate effectiveness of the three innovation policies, the authors observe that none of them is able to generate the mitigation efforts needed to stabilise the CO_2 concentration in the atmosphere as a stand-alone policy. The best long-run performance with respect to fossil fuel emissions comes from IP3, followed by IP2. IP1 has almost no effects, since it is too expensive at the margin and does not help significantly to decarbonise the economy. The largest cumulated emissions reduction that can be achieved as compared to the baseline scenario throughout the century with IP3 is around 13%-14%.

When a climate stabilisation policy is introduced without any innovation policy, investment into R&D rises significantly, since the social planners of each region anticipate the increasing carbon price. Under a 450 ppm CO_2 concentration stabilisation target, the carbon price increases up to \$400 t/CO_{CO}e in 2055 and reaches \$1000 t/CO_2e in 2100. The bulk of the investment goes to backstop technologies, while the investment share dedicated to energy efficiency stays relatively modest. By investing more in advanced technologies throughout the first decades it is possible to significantly reduce future mitigation costs.

Combining innovation policies and carbon pricing policies, the authors compare the cooperative equilibrium - where a global carbon price goes along with a global R&D investment strategy - to the Nash-type equilibrium, where cooperation happens only on the climate policy side. They find that R&D expenditures are higher and costs of climate mitigation are 10% lower when regions cooperate in both climate and innovation policies.

Since the assumption of worldwide cooperation on carbon prices and innovation policies is rather unrealistic, these 10% have to be seen as an upper bound. A sounder policy scenario forecasts a mitigation cost reduction of around 3 - 3.5% at a cost of 0.07% of GWP.

The key message of this paper is that none of the considered innovation policies is able to stabilise the atmospheric CO_2 concentration by its own and that investment into advanced, breakthrough technologies shows the best long-run performance. Mitigation costs can be significantly reduced by combining environmental and innovation policies and by investing in earlier decades.

3.3 Model by Grimaud et al.

Grimaud et al. (2011) follow a general equilibrium approach where they decentralise Popp's ENTICE-BR (Popp (2006)) model in order to study different combinations of innovation and environmental policies. In this model, a final good is created from capital and energy which itself is produced from two primary sources: carbon-emitting fossil energy and carbon-free renewable energy. The CO_2 emissions resulting from the combustion of fossil fuels can be cut down by means of a CCS device. Residual emissions accumulate in the atmosphere causing the global average temperature to rise. This temperature variation is captured by a damage function which reduces the production level. The damage function takes into account both, gradual low to medium scale damages and irreversible catastrophic damages, modelled by an atmospheric CO_2 ceiling that cannot be exceeded.[12]

By investing into the three different endogenous R&D sectors it is possible to increase the efficiency of energy production, renewables and CCS, respectively. The final production is divided up between consumption, direct capital investment, primary energy production, carbon capture and R&D investment, which develop the knowledge stocks devoted to different energy technologies. The model is shown in Figure 4 below.

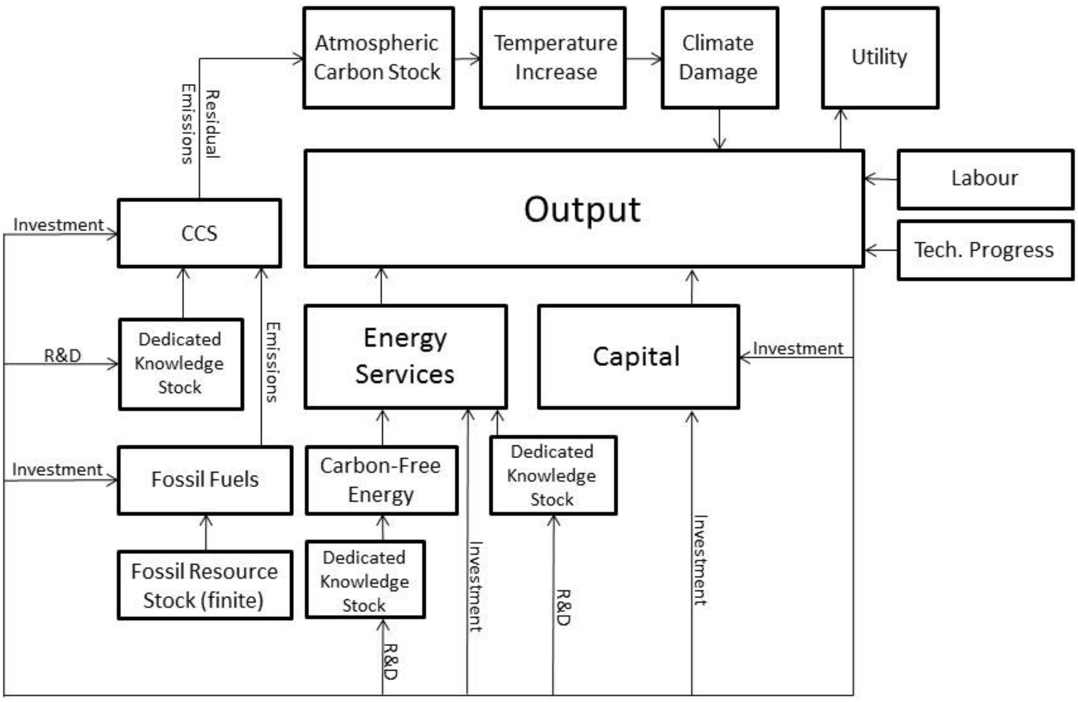

Figure 4: Description of the Model by Grimaud et al.

[12] The thresholds considered are 550 ppm and 450 ppm, which correspond to temperature rises of about 2°C and 3°C respectively compared with the temperature levels in 1990.

The authors analyse the impact of a carbon tax and research subsidies on the level of investments allocated to each R&D sector, the composition of the energy-mix, the climate, and economic growth (regarding the production of the final goods).

Assuming a discount rate of 5%, the optimal tax would initially amount to $49 per tonne of carbon before being regularly increased to reach $256 in 2105. Imposing a stabilisation objective of 550 ppm requires the implementation of a tax that starts at $73, gradually rises to $550 in 2075 and then declines, once the concentration limit has been reached. The more restrictive the limit, the faster the tax will increase over the short-term. Contrary to the Porter Hypothesis and to the findings of Otto and Reilly (2008) in the first model, the implementation of a carbon price alone is insufficient to stimulate research, regardless of the sector in question. A system of subsidies devoted to each of the three sectors must be associated to create incentives.

The enforcement of a carbon tax alone would have no effect on the use of renewable energy, whereas it would significantly reduce the consumption of fossil fuels. As already noted by Bosetti et al. (2011), stand-alone innovation policies (e.g. linked to carbon-free renewable energies or CCS) would have very little impact on the use of fossil fuels, though they imply strong development of renewable energies in this model. The simultaneous application of environmental and innovation policies produces a complementary effect. This combination reinforces the one-sided effect of the carbon tax on fossil fuel consumption and the one-sided effect of R&D subsidies on the use of renewable energies.

The impact on climate change follows directly from the conclusions on the composition of the energy mix. Without any intervention, this concentration should reach almost 1,000 ppm by the end of the century - a threshold that is considered particularly critical by the Intergovernmental Panel on Climate Change (2007), since it corresponds to a mean temperature rise of 6°C. The unilateral use of research policies makes it practically impossible to reverse this trend. On the other hand, an optimal carbon tax without any stabilisation targets would make it possible to lower this concentration to 850 ppm in 2100 - if used alone - and to less than 800 ppm in combination with clean research subsidies. These values are higher than those suggested by Bosetti et al. (2011), who calculate 700 ppm in their BAU scenario and a reduction to 650 ppm in the case where IP2 or IP3 are implemented.

As for the economic repercussions, the authors estimate the cost of inaction at 5% of the GWP in 2100. The simultaneous implementation of both policies (first best) would reduce this cost to 3.5% and stabilising the atmospheric carbon concentration at 550 ppm could limit damages in terms of final output to 1.8%. The authors also discuss intergenerational social costs for these different scenarios. The carbon tax induces a welfare loss for the first generations and a welfare gain in the long run. The higher the tax, the higher are the costs in the short run and the gains for future generations. R&D subsidies as stand-alone policies lead to a welfare increase which remains relatively low, even if it increases in time. Consequently, the simultaneous use of both instruments results in a better intergenerational distribution of the costs related to climate change mitigation policies.

To sum up, Grimaud et al. (2011) find that a stand-alone carbon tax is unable to incentivise clean R&D activities and that the joint use of carbon taxes and clean energy subsidies is the best available policy-mix for efficient climate change mitigation. The carbon tax is first increasing and falls as soon as the CO_2 concentration ceiling is reached. It induces a welfare loss for the first generations but a welfare gain for future generations through enhanced long-term growth. Postponing action decreases this welfare-gain.

3.2 Model by Acemoglu et al.

The main differences in Acemoglu et al. (2012) as compared to the previous models lie in its macroeconomic feedback and in how it accounts for innovation. The authors use a two-sector model of directed technical change and examine how different technologies respond to environmental and innovation policies. The final good is directly produced from two primary sources – carbon-producing ‘dirty’ inputs and carbon-free ‘clean’ inputs – which eliminates the intermediate sector of energy services and renders the need for capital superfluous. In this model three incentives to innovate are considered: the direct productivity effect, the price effect and the market size effect. The first effect leads to innovation in the more productive sector, the second directs innovation to the sector with the higher price and the third enhances innovation in the sector with higher employment. The model is depicted in Figure 5.

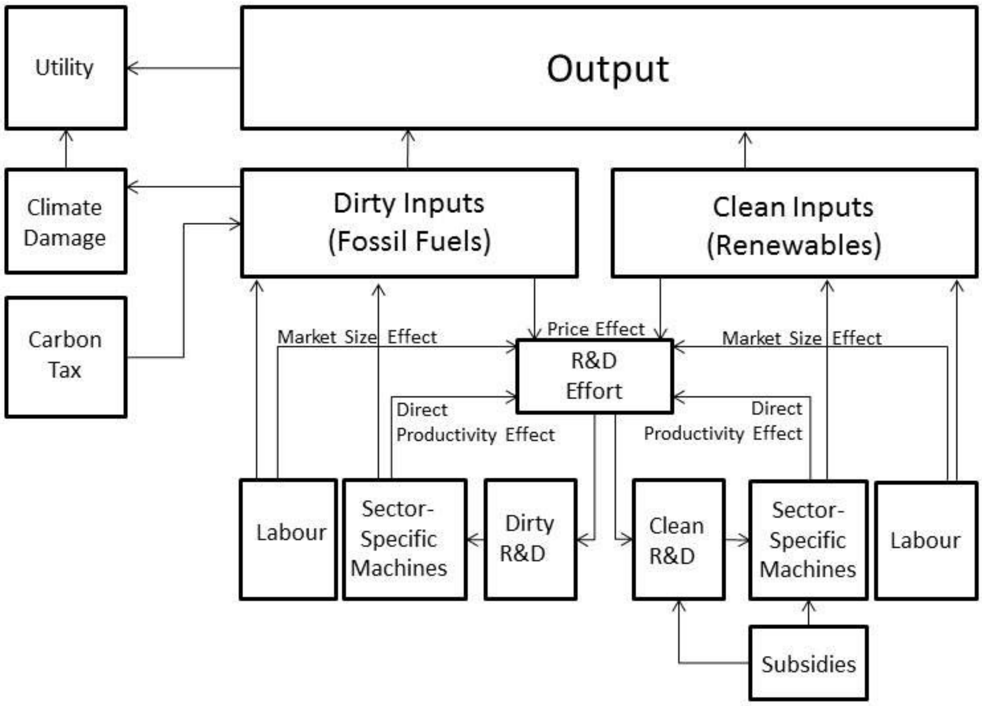

Figure 5 – Model by Acemoglu et al. (without Exhaustible Resources)

Scientists can decide to direct their research effort to two R&D fields. The first field focuses on innovations in the clean sector, like e.g. increasing the efficiency of renewables (as in Grimaud et al. (2011) and Bosetti et al (2011)). The second field is dedicated to research in the dirty carbon-emitting sector, like e.g. fossil fuels. The approach advocated in this model provides a direct analysis of the way in which research adjusts to the two technologies. It also shows a different way of modelling R&D, since innovations no longer result from a process of knowledge accumulation as in the other three models. Instead, innovations are designed as quality improvements of intermediate goods (machines). Like in Gerlagh et al. (2009), successful scientists can secure their innovation by a one-period patent, such that the market they are interacting in is subject to monopolistic competition.

One environmental and two innovation externalities are taken into account. The environmental externality results from the use of dirty inputs which decrease the environmental quality and therefore have a negative impact on social welfare. The innovation externalities come from the monopolistic market structure on the one hand and from underinvestment in the clean research sector on the other hand (standing on shoulders of giants).

Like in the previous models, the authors discuss the optimal regulation of these externalities by setting up a carbon price (here in form of a lump sum tax) and subsidies in the clean input sector. Their analysis focuses on two main aspects: the energy transition and the timing of public action. The results can be summarised as follows:

Fossil fuels have the comparative advantage that they are cheaper and already well-established. For this reason carbon-free energy technologies will never be able to catch up without government intervention, whether through direct aid to production or through clean R&D subsidies. The easier old technologies can be substituted by new ones, the more efficient these public support policies will be. Simulations show that when clean R&D is greatly subsidised in the beginning, it requires much less subsidies in the future, once the clean technologies have been adopted. Furthermore - and in line with Grimaud et al. (2011) - the carbon tax could be reduced over time.

Like in the previous models, a carbon price needs to be fixed together with clean R&D subsidies in order to efficiently stimulate the emergence of new carbon-free energy technologies. The model also shows that used alone, the carbon tax is higher than under joint use with R&D subsidies.

Finally – like Stern (2007) – the authors stress the importance of timing as far as governmental interventions are concerned. It is always costly to wait before launching a carbon tax to efficiently correct for externalities. They also state that the optimal solution would be to direct research to carbon-free technologies as quickly as possible (see also Aghion et al. (2009)). Without stimulating clean research, the economy will continue to further develop fossil fuels. Since fossil fuels will keep their leading edge over clean technologies, the cost of the energy transition will increase. A longer transition period characterised by slower growth would therefore be necessary for the substitution to take place. Figure 6 shows the cost of postponing the implementation of an optimal policy with a discount rate of 4% and 5.5%, respectively. As expected, the benefits of early intervention decrease significantly with an increase of the discount rate.

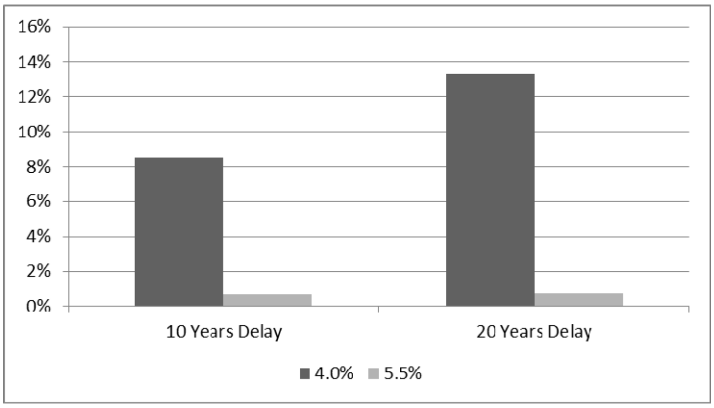

Figure 6: Cost of postponing (% of loss of consumption) in relation immediate action.

In a nutshell, the authors show that an optimal policy-mix consists of both carbon taxes and research subsidies. Postponing action is costly, since it increases the transition phase of slow growth. Furthermore, when clean and dirty inputs are highly substitutable, R&D resources should be directed to the clean research field as soon as possible in order to capture a higher policy response.

4. Conclusion

One of the key objectives of environmental economics is to identify market imperfections and to provide decision-makers with economic tools that can correct them. By comparing different trajectories of public policies, top-down endogenous growth models with a long-term climate damage function can provide useful support for international negotiations on climate issues.

We have compared four top-down endogenous growth models that take into account externalities coming from both pollution and innovation. Although the way how they take into account endogenous technical change varies from one model to another, all of them show that the optimal long-term solution with respect to climate change and social welfare is to simultaneously put in place both a carbon price (in terms of a tax or an emission trading scheme) and research subsidies for carbon-free energy technologies. Furthermore, in line with Stern (2007) and contrary to Goulder and Mathai (2000) all of them emphasise the need for early action in order to reduce the social costs of climate change mitigation.

Using models to gauge the long-term consequences of any public action on climate change and the world economy is certainly subject to controversy. The foresightful analysis must be able to take into account disruptions, which can be a complex process when a model based on formalised relationships is used (Taverdet-Popiolek (2009)).

Yet, different climate or renewable energy targets are regularly conveyed through concrete figures in international negotiations - e.g. factor of 2 by 2050 on a global scale - and economic instruments such as carbon prices and research subsidies have considerable impacts on short- and long-term investment decisions.

We have seen that the descriptions of energy technologies in top-down models are not as detailed as in bottom-up models. Most of the time, the main distinction made is between carbon-based technologies and carbon-free technologies, sometimes including carbon capture and sequestration. Therefore, the recommendation for subsidising clean energies is not necessarily earmarked, depending on the type of solution. More specifically, except for the model of Bosetti et al. (2011), there is no trade-off between nuclear energy and renewable energies and the models could be refined in this direction.

The issue of research efficiency is integrated into the models discussed in this article thanks to innovation functions that create a link between R&D expenses and innovation, weighed by a given probability of success. The innovation process is actually 'smoothed' and takes into consideration a mean arrival rate for innovations rather than the real stochastic process from which it is derived. This approach is possible under the condition that the innovations in question are incremental, i.e. they make it possible to improve the efficiency of an already-existing technical base. Like Romer (1990), we can therefore reasonably assume that, based on the law of large numbers, an innovation is created at every moment with a non-zero probability. By aggregating these incremental arrivals on a sector level, a mean process is obtained which illustrates the continuous arrival of innovations. Except of Bosetti et al. (2011), these models are also limited by the fact that they do not take into account breakthrough or drastic innovations (Helpman (1998) still calls them ‘general purpose technologies’) in the energy sector. Such innovations would therefore occur in a completely stochastic manner, given an instantaneous probability of discovery that evolves over time and that is positively associated with the level of research effort, which would provoke 'leaps' in the main economic trajectories (Lafforgue (2008)).

Another big challenge that should be addressed in future works is the important role of uncertainty on both, the environmental and the innovation side. Although the understanding of climate change has significantly improved in the last decades, the link between the GHG stock in the atmosphere and the global temperature increase remains uncertain. Furthermore, the consequences of this temperature increase are not perfectly understood which makes it difficult to translate the changes into a damage function. As far as the economic side is concerned, the random process of innovation is an obstacle to perfectly forsee the future state of technology. As a recent example for an unexpected technical breakthrough one could name the shale gas revolution that started in the U.S.; others could result from CCS or fast breeder reactors in the future. Although R&D subsidies directed to carbon-free energy technologies are a prerequisite for breakthroughs, they are far from being a guarantee.

Reviewing the literature on uncertainty and endogenous technical change, Baker and Shittu (2008) conclude that modelling uncertainty has important quantitative and qualitative impacts and that optimal R&D investments can increase or decrease with uncertainty, depending on the technology under scrutiny. Using a similar model as Otto and Reilly (2008), Löschel and Otto (2009) introduce uncertainty on the arrival of the CCS technology, but likewise they do not discuss the role of technology policies. They find that the social loss is lower when CCS is not anticipated. None of these studies enters explicitly in the discussion of the interaction between environmental and innovation policy instruments in the presence of uncertainty, a field that should certainly be explored through future research.

Uncertainties both on the innovation process and on climatic feedbacks or the damage function represent additional distortions and require specific regulation tools such as insurances, future or option markets. However, in a world mainly governed by precautionary effects, R&D subsidies and carbon prices through taxes or trading schemes can also be able to partially tackle the problem of uncertainty. Since uncertainties on innovation would lead to a reduction of R&D investments, subsidies could offset this effect. As far as climatic uncertainties are concerned, one could point to the fact that people usually dislike risks and would be willing to reduce their exposure to them. A carbon price could act in the right way.

In line with previously mentioned limitations, it is also challenging to define policies that follow innovations from changes in the whole organisation of the energy systems like energy storage, smart grids or new consumer behavioural patterns. This would at least require to detail the energy technologies (production, networks and utilisations) and to take into account disruptions and regional specificities. Energy issues will continue to play a crucial role in the near and far-distant future and economists can greatly contribute to the implementation of better policy designs. Within this context, endogenous growth models with directed technical change have still much to say.

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