Directed technical change in clean and dirty technologies: Is it possible to redirect R&D in a multi-region world?

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Abstract

In order to stabilize the climate, environmentally friendly energy sources must be developed and improved. The theory of technological change and endogenous growth are crucial when it comes to dealing with the climate issue. If the improvements in technology can be directed to the clean energy sources, it might be possible to solve the climate problem without sacrificing a considerable amount of long-run growth.

This thesis builds on the model by Acemoglu et al (2012), which is an endogenous growth model with directed technical change. It is a two-sector model with clean and dirty technologies that are improved by R&D. The model involves a social planner that can use a carbon tax and/or a research subsidy in order to conduct the optimal policy. I have extended the model into a two regions framework, where only one of the regions has environmental concerns. I have investigated by the use of numerical analysis if it is possible to redirect R&D in a multi-region world.

This thesis concludes that it is possible to redirect R&D by using a subsidy if the environmental concerned region can target more than 50% of the scientists. It will also be possible by using only a carbon tax if the technology gap between the two sectors is not too large. These results suggest that if the majority of the world can agree upon a climate agreement, it will be sufficient to redirect the technological change towards the environmentally friendly energy sources, which again can solve the climate issue.

Preface

First and foremost, I would like to thank my supervisor Mads Greaker at Statistics Norway for outstanding guidance during the writing of this thesis. His great knowledge, valuable feedback and inspiring enthusiasm have been invaluable.

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Ingrid Semb Weyer

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Content

1 Introduction

In 1979 the first World Climate Conference took place in Geneva. The purpose was “to foresee and prevent potential man-made changes in climate that might be adverse to well-being of humanity” (UNEP and UNFCCC 2002). The conference was sponsored by World Meteorological Organization (WMO) and led to the establishment of the World Climate Programme.

In 1988 the Intergovernmental Panel on Climate Change (IPCC) was established by the WMO and the United Nations Environment Programme (UNEP). The IPCC works on giving the world the best scientific, technical and socio-economic information relevant to climate change.

The United Nations Framework Convention on Climate Change (UNFCCC) was ratified in 1992. It is an international environmental treaty whose objective is to prevent climate change by stabilizing greenhouse gas concentrations in the atmosphere (UNFCCC 1992). The agreement set no binding limits for emissions for individual countries, so it is considered legally non-binding.

In 1997 the Kyoto Protocol was adopted. This protocol linked to the UNFCCC was the first substantial climate agreement. It commits its parties by setting “country-specific GHG emissions limits and a timetable for their attainment” (Perman et al, 2011, p. 334). The protocol places most of the responsibility on industrialized nations and sets emission targets for developed countries only (UNFCCC 1998).

Today there are 192 parties to the Kyoto agreement. It is criticized for not binding developing countries to any emission targets, which is one of the main reasons why the US is not participating. From November 30th to December 11th 2015 the UN will arrange a new climate conference in Paris, where the goal is to achieve a new international climate agreement in order to keep the global warming below 2 degrees.

The IPCC’s latest contribution The Fifth Assessment Report (AR5) that was released in four parts in 2013 and 2014, states that: “Human influence on the climate system is clear, and recent anthropogenic emissions of green-house gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (IPCC 2014). The report states that in order to maintain global warming below 2 °C, the GHG emissions must be reduced by 40% to 70% by 2050 compared to 2010, and the emissions levels must be near zero in 2100.

Climate stabilization can be costly if it means reducing long-run growth. The alternative is to develop energy sources that do not emit carbon dioxide to the atmosphere. Hoffert et al (2002) have looked at technology paths to global climate stability. They conclude that: "A broad range of intensive research and development is urgently needed to produce technological options that can allow both climate stabilization and economic development". This means that in order to stabilize the climate, environmental friendly technologies need to be improved.

The technologies in the energy sector can be divided into two groups: Clean and dirty. Clean technologies are low-emission technologies such as solar and wind, electric cars and advanced biofuel, while dirty technologies are high-emission technologies such as coal power plants and internal combustion engines. Currently the clean technologies are at a disadvantage in terms of cost and quality. This thesis will look into how to cause faster improvements in clean technologies than in dirty technologies in a global framework where countries have different preferences. My research question is: Is it possible to redirect R&D in a multi-region world?

This thesis is based on the model by Acemoglu, Aghion, Bursztyn and Hemous (2012), which from now on will be referred to as the AABH model. It is an endogenous growth model for a global economy. The model proposes a simple two-sector model for R&D, where research is divided between clean and dirty technologies. A final good is produced using the inputs produced by these two sectors, and the research will be directed to the most profitable sector.

The AABH model looks at a global economy with a social planner, but this is not the reality in the world today. In this thesis I will introduce two regions, one that care for the environment, while the other one does not want to take the environmental issue into consideration just yet. I will assume that both regions are engaged in R&D, and technology flows between them. The incentives to innovate depend on the aggregate market for dirty and clean intermediates in the two regions.

This thesis will provide a numerical analysis of the two regions framework. It will calculate the optimal policy for the two regions in the business as usual situation and when there is a carbon tax and/or a research subsidy available. All the numerical simulations are conducted in Microsoft Excel 2010.

The rest of the thesis is structured as follows: The next chapter briefly presents some of the literature related to the AABH model. In chapter 3 the AABH model and its results are described in detail. Chapter 4 presents a two regions model that I have developed from the framework of AABH. In chapter 5 all the numerical analysis are made and results are presented. Chapter 6 concludes and summarizes the results of this thesis.

2 Literature Overview

The AABH model builds on two stands of literature: Endogenous growth theory and climate policy with endogenous technical change. In endogenous growth theory "the rate of technological progress, and hence the long-run rate of economic growth, can be influenced by economic factors" (Howitt 2008). Endogenous technical change means that technological improvements take place through innovations, which again is determined by economic factors and policies.

Two of the most cited contributions to endogenous growth theory are the work of Romer (1990) and Aghion and Howitt (1992). In Romer innovation is driven by researchers discovering new intermediate input varieties making it possible to expand production continuously. Aghion and Howitt presented a model of growth through creative destruction. They showed that the profits from current research could be destroyed by future research, which discourages innovations. In their model new innovations improve the quality of existing products, which is the framework adopted by AABH.

The other stand of literature investigates optimal climate policy when technical change is based on R&D or learning by doing effects, see for instance Goulder and Mathai (2000) and Grübler and Messner (1998). A later contribution to this field is Greaker and Pade (2009) who investigated the relationship between emission taxes and technological change. Their model has only one research and development sector (no dirty R&D), and they considered a case without any form of R&D subsidies. They found that when the technological change was endogenous and driven by R&D, the carbon taxes should be higher than if the technological change was exogenous.

The AABH model is an endogenous growth model with directed technical change, which implies that the research will be directed to the most profitable sector. It is a two-sector model where technological change is based on R&D. The model considers both a carbon tax and a subsidy to R&D. The major claim in AABH is that R&D subsidies to clean technologies are more important than carbon taxes when environmental concerns are being considered. In traditional environmental economics the carbon tax plays an important role when correcting for the environmental externality, see for instance Nordhaus (2008), so this result is quite controversial.

There are several properties of the AABH model that could be discussed. In the AABH framework a patent only lasts for one period. Greaker and Heggedal (2012) examined this assumption by introducing long-lived patents into the AABH model. They also find that R&D should be redirected to the clean technologies. However the carbon tax plays a more important role with long-lived patents. Greaker and Heggedal have also developed a numerical model which this thesis will build upon.

Some may object to dividing technologies into clean and dirty. However there are two empirical papers that confirm the assumptions of the AABH model. Dechezleprêtre et al (2013) compared the knowledge spillovers from clean and dirty technologies. Their empirical analysis shows that clean technologies induce larger knowledge spillovers than dirty technologies, which justify higher subsidies for clean R&D. Aghion et al (2012) analysed directed technical change in the auto sector using panel data. Their analysis showed strong evidence for path dependency, which means that firms that are more exposed to clean innovations, are more likely to direct their research to the clean sector. If a firm has a history of clean innovation, it will probably focus on clean research in the future as well.

Based on the discussion above, I conclude that the AABH model seems robust, and this is the reason why it is chosen for this analysis. The AABH model is described in detail in the next chapter.

3 The AABH model

3.1 Directed technical change in clean and dirty technologies

In the paper The Environment and Directed Technical Change AABH presents a global two-sector model with a unique final good. The final good is produced using clean and dirty inputs, where the production of the dirty input creates environmental degradation. The two inputs are produced using labour and sector specific machines, provided by monopolistically competitive firms. Scientists build on previous innovations and try to improve the quality of the machines. If a scientist is successful in innovating a better version of a machine, he/she obtains a one-period patent and becomes the entrepreneur for the current period in the production of that machine. The scientists choose which sector to direct their research against in order to maximize their expected profit.

The dirty input production increases the temperature due to a larger carbon stock. When the temperature increases, environmental quality goes down. If the environmental quality falls below a critical threshold, an environmental disaster will happen, and the utility of the consumer goes to minus infinity.

The AABH model is a growth model with endogenous and directed technical change. This means that the scientists are not randomly allocated between the two sectors, but direct their research to the most profitable sector in the economy. The model studies the technological response that follows from different environmental policies, where the intention is to avoid an environmental disaster.

One of the main results of AABH is that if the two sectors are highly substitutable, carbon taxes and research subsidies can redirect technical change. These policy instruments are only needed until the clean sector catches up with the technology level in the dirty sector. This means that an environmental disaster can be avoided without sacrificing a considerable amount of long-run growth.

3.2 Model description

This section presents the general framework of the AABH model. It will go through all of the production sectors: Final good, intermediates and machines, in addition to the innovation sector. It will also state the consumer preferences and the environmental constraints.

Production:

Final good:

There is a unique final good Y_t produced in a competitive market using clean and dirty inputs, Y_{ct} and Y_{dt}. The production function of the final good is:

(1) $$Y_t = (Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}})^{\frac{\varepsilon}{\varepsilon-1}} ,$$

where t denotes time and ε is the elasticity of substitution between the two inputs. When $\varepsilon > 1$ the two inputs are gross substitutes, and when $\varepsilon < 1$ they are gross compliments. I will from now on assume that $\varepsilon > 1$, which indicates that clean technologies can substitute for dirty technologies. The price of the final good is normalized to 1 so that:

(2) $$[p_{ct}^{1-\varepsilon} + p_{dt}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} = 1,$$

where p_{ct} and p_{dt} are the prices of the clean and dirty inputs.

The production function (1) is constant returns to scale. Thus, the quantity Y_t is decided by demand, and the final good producers choose the use of the two input factors according to the following cost minimization problem:

(3) $\min_{Y_{ct},Y_{dt}}\{p_{ct}Y_{ct}+p_{dt}Y_{dt}\}$,

given that $Y_t=(Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}}+Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}})^{\frac{\varepsilon}{\varepsilon-1}}$,

taking the input prices as given. The first order conditions with respect to the two inputs are given by:

(4) $$\gamma\frac{\varepsilon}{\varepsilon-1}\left[Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}}+Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}-1}\times\frac{\varepsilon-1}{\varepsilon}Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}-1}-p_{ct}=0,$$

(5) $$\gamma\frac{\varepsilon}{\varepsilon-1}\left[Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}}+Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}-1}\times\frac{\varepsilon-1}{\varepsilon}Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}-1}-p_{dt}=0,$$

where γ is the Lagrange multiplier. From the first order conditions it follows that the producers will use a combination of clean and dirty inputs according to:

(6) $$\frac{p_{ct}}{p_{dt}}=\left(\frac{Y_{ct}}{Y_{dt}}\right)^{-\frac{1}{\varepsilon}}.$$

The AABH model assumes that initially the clean sector is sufficiently backward relative to the dirty sector, so $p_{ct}>p_{dt}$. This means that when producing the final good, the dirty input will be used more than the clean.

Intermediate:

The two inputs Y_{ct} and Y_{dt} are produced using a continuum of sector specific machines and labour:

(7) $$Y_{jt} = {L_{jt}}^{1-\alpha} \int_0^1 {A_{jit}}^{1-\alpha} {x_{jit}}^{\alpha} \, di,$$

where $\alpha \in (0,1)$, A_{jit} is the quality of the machine of type i used in sector j $\in \{c, d\}$ at time t, x_{jit} is the quantity of the machine used, and L_{jt} is labour in each sector. That the machines are sector specific means that if a machine is used in the clean sector, it will not be used in the production of the dirty input. Following Greaker and Heggedal (2012), the producers of the intermediates maximize their profits under competitive conditions according to:

(8) $$\max_{L_{jt}, x_{jit}} \left\{ (p_{jt} - \tau_{jt}) Y_{jt} - w_t L_{jt} - \int_0^1 p_{jit} \, x_{jit} \, di \right\},$$

where w_t is the wage at time t, τ_{dt} is the carbon tax ($\tau_{ct} = 0$) and p_{jit} is the price of machine type i used in sector j $\in \{c, d\}$. When inserting for Y_{jt} from (7), (8) can be written as:

(9) $$\max_{L_{jt}, x_{jit}} \left\{ (p_{jt} - \tau_{jt}) {L_{jt}}^{1-\alpha} \int_0^1 {A_{jit}}^{1-\alpha} {x_{jit}}^{\alpha} \, di - w_t L_{jt} - \int_0^1 p_{jit} \, x_{jit} \, di \right\}.$$

From the first order condition the demand for machine type i is given by:

(10) $$x_{jit} = \left(\frac{(p_{jt} - \tau_{jt})\alpha}{p_{jit}} \right)^{\frac{1}{1-\alpha}} L_{jt} A_{jit}.$$

The market clearing condition for the labour market requires that labour demand in both sectors must be equal to total labour supply:

(11) $$L_{ct} + L_{dt} = 1,$$

where total labour supply is normalized to one.

Machine producers:

In both sectors monopolistically competitive firms supply the machines. The machine producers solve the following maximization problem:

(12) $$\max_{p_{jit}} \{p_{jit}x_{jit}(p_{jit}) - \psi(1-s)x_{jit}(p_{jit})\},$$

where x_{jit} is a function of p_{jit} given by (10). It costs ψ units of the final good to produce one unit of any machine, and s is the subsidy rate to correct for the monopoly distortion[1]. The first order condition with respect to p_{jit} is:

(13) $$p_{jit} = \frac{\psi\,(1-\mathrm{s})}{\alpha},$$

which gives the machine price. The model assumes $\psi \equiv \alpha^2$ and inserting for p_{jit} from (13), (10) can be rewritten as:

(14) $$x_{jit} = \left(\frac{(p_{jt}-\tau_{jt})}{(1-\mathrm{s})}\right)^{\frac{1}{1-\alpha}} L_{jt}A_{jit},$$

[1] A monopolist will set the price too high and the quantity to low compared to the social optimum.

where x_{jit} is the demand for machine type i used in sector j.

Greaker and Heggedal (2012) have shown that the optimal subsidy rate that gives price equal to marginal cost is $s = 1 - \alpha$. The equilibrium profits of machine producers are then found using (12) - (14) and can be written as:

$$(15) \qquad \pi_{jit} = (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jt} - \tau_{jt})^{\frac{1}{1-\alpha}} L_{jt} A_{jit}.$$

This expression is essential; it gives the per period profit of holding a patent on machine type i used in sector j. It will be discussed in further detail under the innovation part.

Consumption:

The AABH model considers an infinite-horizon discrete time economy with one infinitely-lived representative consumer. The representative consumer has preferences given by:

$$(16) \qquad \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t}\, u(C_t, S_t),$$

where C_t is consumption of the final good, t denotes time and ρ is the discount rate. $S_t \in [0, \overline{S}]$ measures the environmental quality, where $\overline{S}$ is the maximum level which is obtained when there is no human pollution.

The consumer's preferences are of the Ramsey type, where the infinitely-lived consumer represents a family covering all generations. The term $\frac{1}{(1+\rho)^t}$ is the discounting function of future periods, which may be interpreted as the probability of the world's existence at time t.

Since there is no saving between periods, the market clearing for the final good implies that:

$$(17) \qquad C_t = Y_t - \psi \left(\int_0^1 x_{cit}\, di + \int_0^1 x_{dit}\, di \right),$$

where C_t is consumption of the final good. The production of the final good in one period is used for consumption in the same period, except the units that are used in machine production.

The utility function is increasing in consumption and environmental quality. It is twice differentiable and jointly concave in (C, S). The AABH model imposes the following conditions:

$$(18) \qquad lim_{C\downarrow 0} \frac{\partial u(C,S)}{\partial C} = \infty, \quad lim_{S\downarrow 0} \frac{\partial u(C,S)}{\partial S} = \infty, \quad lim_{S\downarrow 0}\, u(C,S) = -\infty,$$

meaning that when the environmental quality goes towards zero, the utility consequences for the representative consumer will be severe. The model also assumes:

$$(19) \qquad \frac{\partial u(C,\bar{S})}{\partial S} = 0,$$

which implies that when the environmental quality is at its maximum level, the value of a further marginal increase will be zero.

The environment:

The environmental quality S_t evolves over time according to:

(20) $$S_{t+1} = -\xi Y_{dt} + (1+\delta)S_t,$$

as long as the right hand side of (20) is in the interval (0, $\overline{S}$). If it is greater than $\overline{S}$, $S_{t+1} = \overline{S}$, and if the right hand side is negative, $S_{t+1} = 0$. The parameter ξ is the rate of environmental degradation resulting from the dirty inputs production, while δ is the rate of environmental regeneration measuring how much pollution the nature can neutralize. If the environmental quality becomes critically low to a point of no return, we have what is defined as an environmental disaster. This happens if $S_t = 0$ for some $t < \infty$.

Innovations:

There is an innovation sector divided between clean and dirty technology. At the beginning of every period each scientist decides which sector to work in, and they are then randomly allocated to at most one machine. The scientist is successful in innovation with probability $\eta_j \in (0,1)$ in sector $j \in \{c, d\}$. A successful innovation increases the quality of a machine from A_{jit} to $(1+\gamma)A_{jit}$, where $\gamma > 0$. If a scientist is successful in innovating a better version of machine i, he or she obtains a one-period patent and becomes the entrepreneur for the current period in the production of that machine. In sectors where innovation is not successful, a randomly chosen entrepreneur will receive the monopoly rights and then use the old technology.

The machines have different productivity, and the scientists do not know which machine they will be allocated to. When deciding which sector to work in, they therefore base their decisions on the average productivity of the machines in each sector. The average productivity in sector j is given by:

(21) $$A_{jt} \equiv \int_0^1 A_{jit}\, di,$$

and evolves over time according to:

(22) $$A_{jt} = \left(1 + \gamma \eta_j s_{jt}\right) A_{jt-1},$$

where s_{jt} denote the number of scientists working on machines in sector j at time t. The average productivity in sector j today depends on the productivity level in that sector the previous period, the number of scientists doing research in that sector and the probability of a successful innovation. The initial levels A_{c0} and A_{d0} are given, and the AABH model assumes that the clean sector is sufficiently backward relative to the dirty sector.

A scientist will base his decision on the expected profit when deciding which sector to work in. If the scientist is successful in innovation, he/she will obtain a monopoly profit for one period given by (15). The expected profit Π_{jt} for a scientist doing research in sector j at time t is therefore:

(23) $$\Pi_{jt} = \eta_j (1 + \gamma)(1 - \alpha) \alpha^{\frac{1-2\alpha}{1-\alpha}} (p_{jt} - \tau_{jt})^{\frac{1}{1-\alpha}} L_{jt} A_{jt-1}.$$

The expected profit equals the monopoly profit in the last period before the innovation occurs, multiplied with the quality improvement $(1 + \gamma)$ and the probability η_j of a successful innovating in that sector. The profitability increases with the number of workers L_{jt} employed in the sector and with the average productivity of the machines A_{jt-1}. The expected profit of a scientist in sector j is larger the higher the price of the input the sector produces, which is denoted by p_{jt}.

The relative benefit from undertaking research in the clean sector relative to the dirty sector follows from (23) and is given by:

$$(24) \qquad \frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \times \underbrace{\left(\frac{p_{ct}}{p_{dt}-\tau_{dt}}\right)^{\frac{1}{1-\alpha}}}_{price\ effect} \times \underbrace{\frac{L_{ct}}{L_{dt}}}_{market\ size\ effect} \times \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{direct\ productivity\ effect}.$$

The higher this ratio, the more profitable is R&D in the clean sector. AABH define three effects that are affecting the profitability:

1. The price effect, which favours the sector with higher prices. A tax on dirty inputs will therefore favour clean R&D.
2. The market size effect, encouraging innovation in the sector with the larger market for machines when the two input are substitutes. AABH assume that initially there is a larger market for dirty machines, so this effect will favour the dirty sector.
3. The direct productivity effect, which pushes innovations towards the sector with highest productivity. This is due to the standing on shoulders effect given by $(1+\gamma)A_{jit}$, indicating that the productivity improvement is higher the more advanced the sector is. This effect will favour the dirty sector, since AABH assume that initially the clean sector is relatively backwards in comparison.

If the expression in (24) favours the dirty sector, the social planner can introduce a subsidy to make R&D in the clean sector more profitable. The expected profit from undertaking research in the clean sector when there is a research subsidy becomes:

$$(25) \qquad \Pi_{ct} = (1+q_t)\eta_c(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} p_{ct}^{\frac{1}{1-\alpha}} L_{ct} A_{ct-1},$$

where q_t is the subsidy rate. The subsidy is given to successful scientists in the clean sector and is financed through a lump-sum tax on the representative household.

The number of scientists is normalized to 1, and the market clearing condition for scientists requires that each scientist is employed either in the clean or dirty sector:

(26) $$s_{ct} + s_{dt} = 1.$$

Since the expected profit of one scientist is not affected by the choice of the other scientists, all the scientists will choose the same sector. The solution will therefore be a corner solution where s_{ct} or $s_{dt} = 1$.

3.3 Results

This section states the main results of the paper by AABH. It distinguishes between the business as usual equilibrium and the situation with optimal policy intervention.

3.3.1 Laissez-Faire Equilibrium

AABH characterize the laissez-faire equilibrium as the situation without any policy interventions. They assume that initially the dirty sector is more advanced relative to the clean sector, and show that there exists a unique equilibrium where innovations only occurs in the dirty sector. The scientists will direct their research towards the dirty sector in order to maximize their expected profit. A_{dt} will grow, while A_{ct} will remain constant, so the gap between the two sectors will increase even more. The dirty input production Y_{dt} will increase over time which makes the carbon stock larger. Without any policy interventions this leads to an environmental disaster.

3.3.2 Socially optimal allocation

The social optimal allocation must correct for three market failures: The environmental externality from dirty input producers, the knowledge externalities from R&D and the monopoly distortion in the production of machines. AABH shows that this can be done by using a carbon tax, a subsidy to clean innovations and a subsidy for the use of all machines.

The social planner maximizes the utility of the representative consumer using the available policy instruments. The social planner's problem becomes:

$$(27) \qquad \max \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t, S_t),$$

subject to (1), (7), (11), (17), (20), (22) and (26). AABH finds a dynamic path of final good production Y_t, consumption C_t, input productions Y_{jt}, machine productions x_{jit}, labour allocations L_{jt}, scientist allocations s_{jt}, environmental quality S_t, and qualities of machines A_{jit}, which determines the socially optimal allocation.

The optimal policy involves avoiding an environmental disaster by switching the innovations towards the clean sector. When the two inputs are substitutes, all research can be redirected to the clean sector by introducing a R&D subsidy that is sufficiently high. The ratio A_{ct}/A_{dt} will increase, which increases the profitability of the clean sector compared to the dirty sector.

If the two inputs are strong substitutes and initial environmental quality is high enough, an environmental disaster can be avoided by introducing a temporary research subsidy. When the ratio A_{ct}/A_{dt} has become sufficiently high, scientists will direct their research to the clean sector even without a subsidy. However if the two inputs are weak substitutes, temporary research subsidies are not enough due to the price effect. The subsidies need to be permanent in order to avoid an environmental disaster.

An emission tax is used to correct for the environmental externality. This tax reduces the production of the dirty input and discourages innovations in the dirty sector. To only use a carbon tax to correct for both the environmental externality and the knowledge externalities from R&D, would lead to excessive distortions. This would imply a higher carbon tax that would reduce consumption and distort production more than when a R&D subsidy is used as well.

A subsidy for machines is used to correct for the monopoly distortion. In a monopoly situation too few machines are sold due to higher prices. By introducing a subsidy, the price of the machines will go down, and the optimal amount of machines will be used.

AABH uses numerical simulations to illustrate the implications of their findings. The results from the numerical analysis presented in the article by AABH are illustrated in figure 1. AABH considers three different cases $[\varepsilon = 10, \rho = 0{,}015]$, $[\varepsilon = 3, \rho = 0{,}015]$, and $[\varepsilon = 3, \rho = 0{,}001]$.

The optimal environmental policy from AABH

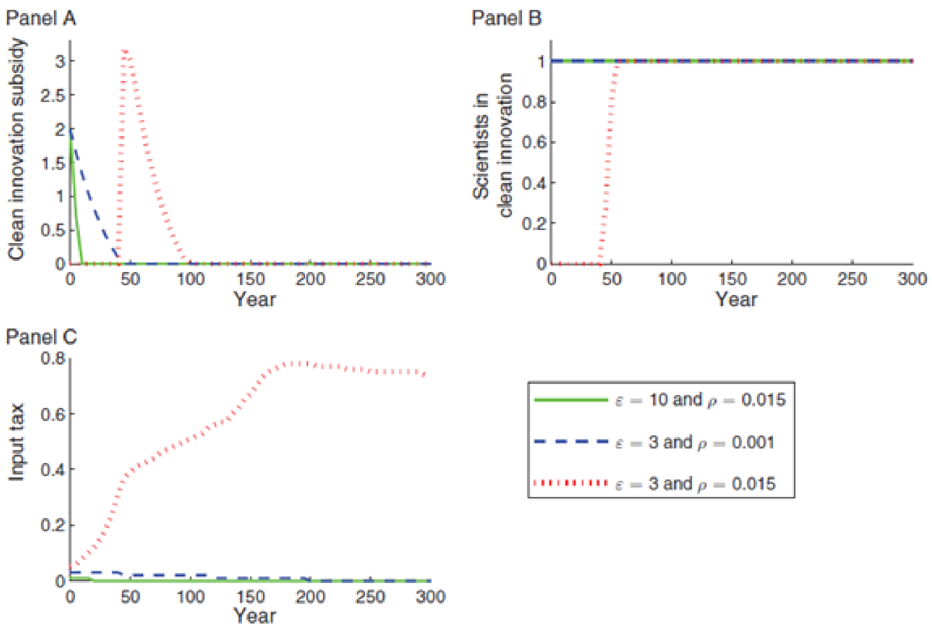

Figure 1: The results from the AABH model. This figure is borrowed from the article by AABH.

Case 1: The situation when $[\varepsilon = 10, \rho = 0{,}015]$ is illustrated by the green (or solid) line. Panel A shows that the optimal subsidy to clean research is decreasing and only temporary.

Panel B shows that the optimal environmental policy involves switching all the scientists towards the clean sector in the first period. In panel C the optimal carbon tax is illustrated. The tax is very low and is only needed for a limited period. This is because the immediate switch to clean R&D makes this tax unnecessary, and because environmental damages are negligible as long as $\Delta_t < 6$°C.

Case 2: The situation when $[\varepsilon = 3, \rho = 0{,}015]$ is illustrated by the red (or small dotted) line. Panel B shows that the optimal shift to clean research occurs around year 50. In panel A the optimal subsidy is larger and last longer compared to case 1. This is because the switch to clean research occurs later. Panel C shows that there is a much higher carbon tax compared to the other cases, and that it will increase over time.

Case 3: The situation when $[\varepsilon = 3, \rho = 0{,}001]$ is illustrated by the blue (or long dotted) line. Panel B shows that all research will be redirected to the clean sector immediately. In panel A the subsidy will be larger than in case 1, but smaller than in case 2. The optimal carbon tax is illustrated in figure C. The tax is very small, but a little higher than in case 1.

The AABH model concludes that when the two inputs are highly substitutable, an environmental disaster can be avoided without sacrificing a considerable amount of long-run growth. This is a more optimistic view than the answers from exogenous technology models and depends on the assumption of endogenous and directed technical change

4 A two regions model

4.1 Model description

The AABH model analyses the whole world as one unit. In this section I will extend the model into two regions, which I name Environmental Concerned (E) and Unconcerned (U). I will assume that only Environmental Concerned cares about the environment. Since countries have different locations, economic situations and resources, it is reasonable that they have different environmental concerns and politics. This is also supported by the lack of an international climate agreement between all countries in the world.

The clean and dirty technologies are not defined in the article by AABH. I will in this model assume that the final good is electricity, and that the two inputs are electricity from clean and dirty production methods. The clean inputs are electricity from sources such as wind, solar and hydro, while the dirty inputs are electricity from sources such as coal, oil and gas. The electricity assumption is made due to its increasing share of total energy demand and its potential for renewables, which is shown by the IEA in the Energy Technology Perspectives 2014[2].

The two regions different environmental concerns are reflected by the preferences of the consumers. Each region will have its own representative consumer, so the global framework will have two representative consumers. The consumer in Environmental Concerned has the same preferences as in AABH, but the consumer in Unconcerned now has preferences given by:

(28) $$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \, u_U(C_{tU}).$$

[2] "Since the 1970s, electricity's overall share of total energy demand has risen from 9% to over 17%" (IEA 2014 p.10). The International Energy Agency predicts that it will continue to rise and be at 25% by 2050. According to their numbers the global share of renewables was 13,2% of the total energy supply in 2012. The share of renewables in electricity generation was almost 22% in 2013, which is a 5% increase from 2012.

which indicates that the utility function of the consumer in Unconcerned is not affected by the environmental quality.

Both regions produce the final good and also the intermediates according to the framework above, so each region will have its own version. The variables subscript will be extended with $r \in \{E, U\}$ that indicates the region. The elasticity of substitution between the two inputs ε will be the same in the two regions. Each region uses their final good for consumption and production of the machines in their own region, so there is no trade. Since we think of Y as electricity, the no trade assumption is reasonable if we look away from trade in fossil fuels and assume coal in unlimited amounts in both regions.

The population in Environmental Concerned/ Unconcerned is employed in either the clean or the dirty sector where they live, so labour is not mobile between the two regions. The market clearing condition for the labour market requires that labour demand in both sectors in one region must be equal to total labour supply in the same region:

(29) $$L_{ctr} + L_{dtr} = \overline{L_r},$$

where $\overline{L_E}$ and $\overline{L_U}$ is total labour supply in Environmental Concerned and Unconcerned. The two regions are endowed with equal amount of labour which is normalized to one, hence $L_E = L_U = 1$. This indicates that the population size is the same in the two regions.

The pollution function is global, and it does not matter if the pollution is done by Environmental Concerned or Unconcerned. The global environmental quality S_t evolves over time according to:

(30) $$S_{t+1} = -\xi(Y_{dtE} + Y_{dtU}) + (1 + \delta)S_t,$$

where Y_{dtE} is pollution from Environmental Concerned, and Y_{dtU} is pollution from Unconcerned. The environmental quality will therefore be the same in the two regions and depend on the total pollution. The properties of this equation will otherwise be the same as in the initial framework.

The scientists have a global perspective and sell their machines to both regions. Each machine is sector specific, so a scientist that obtains a patent on a clean machine becomes the machine producer of that machine in the clean sector in both regions. A_{jit} which is the quality of the machine of type i is therefore the same in both regions, meaning perfect technology transfer. The per period profit of holding a patent on machine type i used in sector j now becomes:

$$(31) \qquad \pi_{jit} = \pi_{jitE} + \pi_{jitU} = (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} A_{jit} \left[(p_{jtE} - \tau_{jtE})^{\frac{1}{1-\alpha}} L_{jtE} + (p_{jtU})^{\frac{1}{1-\alpha}} L_{jtU} \right].$$

The scientists will take the expected profit from both regions into account when deciding with sector to direct their research towards. The expected profit Π_{jt} for a scientist doing research in sector j at time t is therefore:

$$(32) \qquad \Pi_{jt} = \Pi_{jtE} + \Pi_{jtU} = \eta_j (1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} A_{jt-1} \left[\left(p_{jtE} - \tau_{jtE}\right)^{\frac{1}{1-\alpha}} L_{jtE} + \left(p_{jtU}\right)^{\frac{1}{1-\alpha}} L_{jtU} \right].$$

The relative benefit from undertaking research in the clean sector relative to the dirty sector when there are two regions is given by:

(33) $$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \times \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{direct\ productivity\ effect} \times \left\{ \left[\underbrace{\left(\frac{p_{ctE}}{p_{dtE} - \tau_{dtE}}\right)^{\frac{1}{1-\alpha}}}_{price\ effect\ Environmental\ Concerned} \times \underbrace{\frac{L_{ctE}}{L_{dtE}}}_{market\ size\ effect\ Environ.\ Concerned} \right] + \left[\underbrace{\left(\frac{p_{ctU}}{p_{dtU}}\right)^{\frac{1}{1-\alpha}}}_{price\ effect\ Unconcerned} \times \underbrace{\frac{L_{ctU}}{L_{dtU}}}_{market\ size\ effect\ Unconcerned} \right] \right\},$$

where the effects are described in the general framework. Each region will therefore effect the scientists decision through the price effect and market size effect.

The government in Environmental Concerned can introduce a subsidy to clean research in order to make the clean sector more profitable for the scientists. The expected profit from undertaking research in the clean sector then becomes:

(34) $$\Pi_{ct} = \eta_c(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} A_{ct-1} \left[(1+q_{tE})(p_{ctE})^{\frac{1}{1-\alpha}} L_{ctE} + (p_{ctU})^{\frac{1}{1-\alpha}} L_{ctU} \right],$$

where q_{tE} is the subsidy rate in Environmental Concerned. Since Unconcerned does not care about the environment, their subsidy rate to clean research q_{tU} will always be 0.

For simplicity I assume that the Unconcerned region will not try to affect the R&D decision. This assumption will be discussed later in chapter 5. Without this assumption it is possible that the Unconcerned region starts subsidizing dirty R&D in order to neutralize the subsidy from Environmental Concerned.

4.2 Equilibrium condition

In the AABH model the social planner maximizes the discounted utility of the representative consumer as shown above in equation (27). In the two regions framework there will be two social planners, one for each region. The social planners maximize the discounted utility of the representative consumer in its own region using the available policy instruments.

The planner in Environmental Concerned can use a carbon tax, R&D subsidy to clean innovations and a subsidy to machines in order to maximize the discounted utility of its representative consumer. Since the consumer in Unconcerned does not care about the environment, the only policy instrument the planner in Unconcerned will use, is the subsidy to correct for the monopoly distortion. I assume that this subsidy will always take place in both regions in order to focus on the environmental considerations.

In the first period the scientists choose either the clean or the dirty sector in order to maximize their expected profit. Since the expected profit of one scientist is not affected by the choice of the other scientists, all the scientists will choose the same sector. If the social planner in Environmental Concerned wants to redirect innovations towards the clean sector, he/she must make the clean sector equally or more profitable for the scientists compared to the dirty sector.

In order to solve the two regions model, I define the equilibrium condition as the situation where the two social planners maximize the utility of their representative consumers given their policy instruments, and where none of the scientists wish to change their decision in any of the time periods. If all the scientists are in the clean sector, this sector will also be the sector where the expected profit is largest in order for the equilibrium condition to hold. The equilibrium solution will be a corner solution where all the scientists do research in the same sector. This follows from earlier discussion of the corner solution in AABH.

In figure 1 the optimal environmental policy results from AABH are illustrated. In order to solve for the equilibrium solution in the two regions framework, I need to move on to numerical analysis.

5 Numerical model

5.1 Model description

In this section I will use a numerical framework to analyse the two regions model. The model is solved for 28 periods of 5 years each, so the time period is from 2010-2150. The numerical model is an extension of the quantitative example in the article by AABH and the simulations by Greaker and Heggedal.

The evolution in the concentration of CO_2 in the atmosphere is given by:

(35) $$C_{co_2,t+1} = \xi \left(\frac{Y_{dtE}+Y_{dtU}}{2}\right) + (1+d)C_{co_2,t} - 1120d,$$

where $C_{co_2,t}$ is the carbon stock at time t. Greaker and Heggedal set the initial level of the carbon stock to 379 ppm, and I will also use this value. The parameters ξ and d is chosen to yield a reasonable evolution of the carbon stock in the business as usual (BAU) situation. In order to achieve this I use the values $\xi = 4$ and $d = 0{,}00375215$, which is also used by Greaker and Heggedal.

The temperature increase from the concentration of CO_2 is given by:

(36) $$\Delta_t = 3log_2\left(\frac{C_{co_2,t}}{280}\right).$$

This equation from the AABH framework implies that a doubling of CO_2 concentration in the atmosphere leads to a 3°C increase in current temperature.

Environmental quality in AABH is given by:

(37) $$\phi = \phi\big(\Delta(S_t)\big) = \frac{\big(\Delta_{disaster}-\Delta(S_t)\big)^{\lambda}-\lambda\Delta_{disaster}^{\lambda-1}\big(\Delta_{disaster}-\Delta(S_t)\big)}{(1-\lambda)\Delta_{disaster}^{\lambda}},$$

where a disaster is defined as an increase in temperature equal to $\Delta_{disaster}=$ 6°C. $\Delta(S_t)$ is the temperature increase function depending on environmental quality. Greaker and Heggedal have used the direct temperature increase instead, and this is the framework I will follow.

The environmental quality function is therefore written as:

(38) $$\phi_t = \frac{(6-\Delta_t)^{\lambda}-\lambda 6^{\lambda-1}(6-\Delta_t)}{(1-\lambda)6^{\lambda}},$$

where Δ_t is given by (36). If $\Delta_t \geq 6$, then $\phi_t = 0$. In order to match this function with the Nordhaus's damage function for temperature increases up to 3°C, AABH set $\lambda = 0{,}1443$, which is the value I will use.

The utility function used by AABH and Greaker and Heggedal is:

(39) $$u(C_t, S_t) = \frac{(\phi_t * C_t)^{1-\sigma}}{1-\sigma},$$

where ϕ_t is given by (38), C_t is given by (17) and σ is the intertemporal elasticity of substitution. I will use this utility function for the representative consumer in Environmental Concerned. The consumer in Unconcerned thus not cares about the environment so his utility function will be:

(40) $$u_U(C_{tU}) = \frac{{C_{tU}}^{1-\sigma}}{1-\sigma}.$$

AABH set $\sigma = 2$ which matches Nordhaus's choice of intertemporal elasticity of substitution, and I will use this value in the simulations.

The AABH model considers two different values for ε and ρ as illustrated in figure 1. Since I assume that the final good is electricity, I will use $\varepsilon = 10$ which is the high value. This choice is based on the assumption that clean electrical power and dirty electrical power is highly substitutable. I use the same discount rate as Greaker and Heggedal so $\rho = 0{,}015$. The capital share is chosen by AABH to $\alpha = 1/3$, the probability of a successful innovation is the same in both sectors $\eta_c = \eta_d = 0{,}02$ and $\gamma = 1$, so that long-run annual growth rate is equal to 2 percent.

The initial productivity levels A_{c0} and A_{d0} are given. In order to achieve a reasonable business as usual situation the initial values are set to $A_{d0} = 1$ and $A_{c0} = 0{,}8$, which yields a renewable share of 18,428% in period 0. IEA estimates that in 2011 about 21% of world electricity generation was from renewable energy, so these numbers seem reasonable. The simulations are also done for $A_{c0} = 0{,}65$ and $A_{c0} = 0{,}5$ in order to see how the initial productivity gap between the two sectors affects the results.

5.2 Results

5.2.1 Business as usual (BAU)

In the BAU situation no policy instruments are available, so there are no government interventions due to environmental considerations. The government in Environmental Concerned will not subsidize clean R&D, and there is no carbon tax, so $q_{tE} = \tau_{jtE} = 0$.

The scientists will compare the expected profit between the two sectors in the first period. Since the expected profit is higher in the dirty sector in the BAU situation, all the scientists will direct their research towards that sector. The productivity development depends on the number of researchers, and since all scientists are in the same sector, only the dirty machines will have productivity growth. This will make the dirty sector even more profitable compared to the clean, so all the scientists stay in the dirty sector.

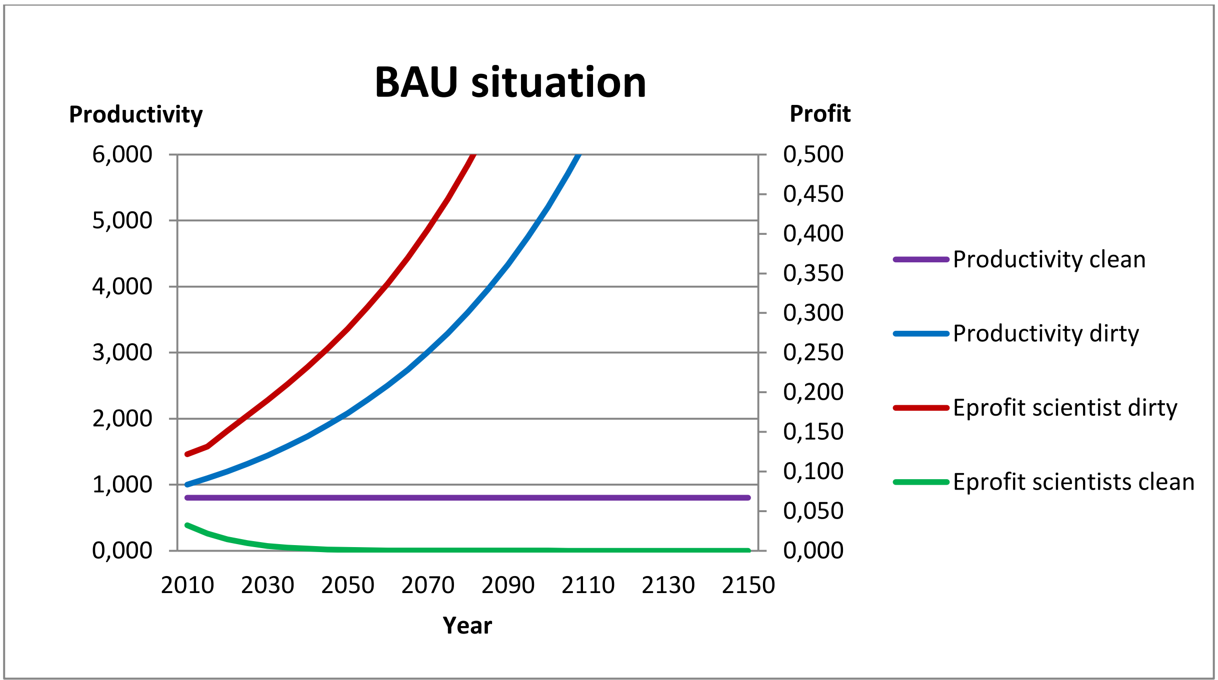

Figure 2: The BAU case shows the development of productivity levels in the two sectors and the expected profit to scientists doing research in the two sectors.

Figure 2 illustrates this situation graphically for $A_{d0} = 1$ and $A_{c0} = 0{,}8$. The left vertical axis measures the productivity level in the two sectors, while the right measures the expected profit for the scientists. The horizontal axis is the timeline between 2010 and 2150. Initially in 2010 the productivity gap is 0,2 and the difference in expected profit is 0.090 between the two sectors. The blue line shows how the productivity in the dirty sector grows over time. The purple line shows how productivity in the clean sector stays constant, since there are no scientists working on clean machines. The red line is the expected profit of a scientist doing research in the dirty sector, and this increase together with the productivity growth. The green line is the expected profit of a scientist in the clean sector, which starts at 0,032 and drops towards zero as time goes by. The profitability of choosing the dirty sector for a scientist will therefore increase over time, so no scientist wish to deviate from the dirty sector. The equilibrium condition holds, so this corner solution is stable.

The two regions have the same production function and will use the same amount of the clean and dirty inputs in the BAU case. As time goes by, the production of the clean input will decrease, and labour will move towards the dirty sector. The firms will use less and less of the clean input and clean machines, and eventually there will be no activity in the clean sector. Since both regions use more and more of the dirty input, the carbon stock will increase and so will the temperature. The amount of consumption will be equal in the two regions in the BAU situation.

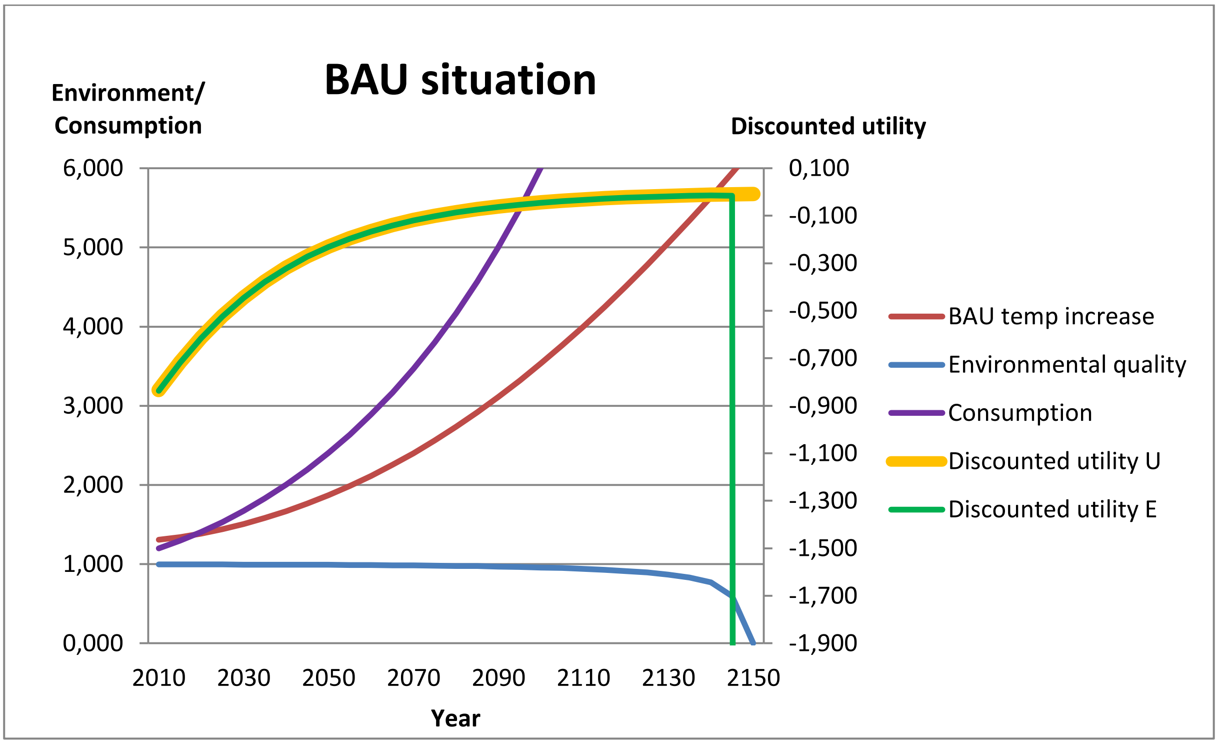

Figure 3: The BAU case shows that without any policy interventions the economy moves towards an environmental disaster.

Figure 3 shows the environmental changes and how these affect the consumers for $A_{d0} = 1$ and $A_{c0} = 0{,}8$. The left vertical axis measures the environmental quality, consumption and temperature increase which is equal in the two regions. The right vertical axis measures the discounted utilities in the two regions, and the horizontal axis is the timeline between 2010 and 2150. The red line is the temperature increase, which increases due to a larger carbon stock as time goes by. The purple line is consumption, which rises over time and is equal in the two regions in the BAU situation. The blue line is environmental quality which decreases as the temperature increases, and it approaches 0 when the temperature increase is 6°C, which is the situation AABH refer to as an environmental disaster. The yellow line is the discounted utility for the consumer in Unconcerned, which increases due to increased consumption. The green line is the discounted utility for the consumer in Environmental Concerned, which follows the yellow line until an environmental disaster occurs. When an environmental disaster happens, the discounted utility for the Environmental Concerned region goes to minus infinity.

In the BAU situation without any policy interventions, the economy is headed towards an environmental disaster with no economic activity in the clean sector. If the initial productivity level in the clean sector is $A_{c0} = 0{,}65$ or $A_{c0} = 0{,}5$ instead of $A_{c0} = 0{,}8$, this result will not change. The consumers will be better and better off until the disaster occurs, but when it happens, it will have severe consequences for the consumer in Environmental Concerned. The interpretation of this can be that one of the regions is more exposed to natural hazards such as storms, earthquakes and sea level rise. The United Nations University and the Alliance Development Works have calculated the World Risk index featured in the World Risk Report 2014, which rank the countries around the world based on their vulnerability and exposure to natural hazards. This report shows that there are large differences between the countries, which may lead to different environmental concerns (UNU-ADW).

5.2.2 Research and development subsidy (R&D)

In the BAU situation the utility of the Environmental Concerned consumer goes to minus infinity when an environmental disaster occurs. In order to avoid this, the government in the Environmental Concerned region can introduce a subsidy (financed through a lump-sum tax on the representative household) to clean research, making the clean sector more profitable for the scientists.

In order to avoid an environmental disaster, the Environmental Concerned region must redirect innovations towards the clean sector. If the expected profit of a scientist is larger in the dirty sector than in the clean, the Environmental Concerned region will introduce a subsidy making the clean sector equally or more profitable compared to the dirty. Since the expected profit is higher in the clean sector with a subsidy from the Environmental Concerned region, all the scientists will direct their research towards that sector. The ratio A_{ct}/A_{dt} will increase, and when it has become sufficiently high, the scientists will direct their research to the clean sector even without a subsidy.

Since the two inputs are substitutes, all research can be redirected to the clean sector by a temporary subsidy that is sufficiently high. How long the government in Environmental Concerned must subsidize the clean sector, and how large the subsidy must be, depends on the initial productivity gap between the two sectors.

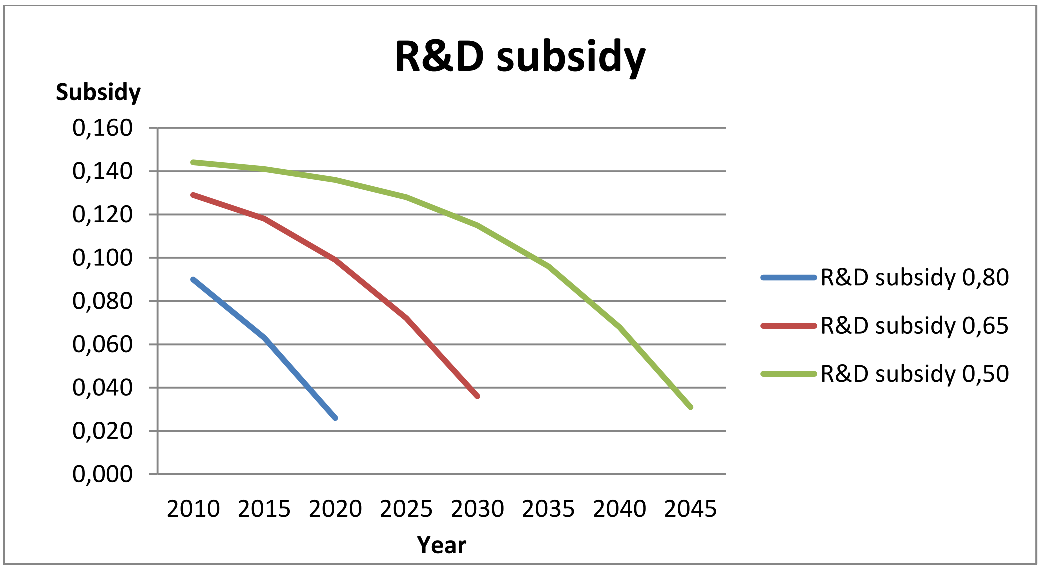

Figure 4a: The subsidy needed to redirect innovations towards the clean sector for different productivity levels.

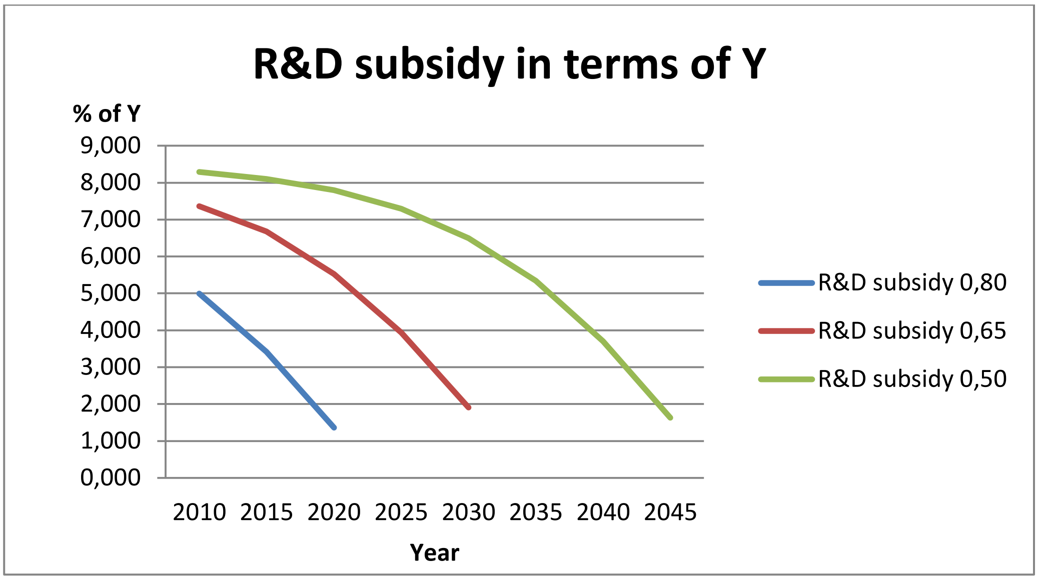

Figure 4b: The subsidy needed to redirect innovations towards the clean sector for different productivity levels, measured in % of Y for the Environmental Concerned region.

Figure 4a illustrates how large the subsidy must be in order to redirect innovations towards the clean sector for the different productivity levels. If $A_{c0} = 0{,}8$, the blue line shows that the subsidy will start at 0,090 in year 2010 and decrease until year 2020. After this period it will be profitable for the scientists to stay in the clean sector even without a subsidy. If $A_{c0} = 0{,}65$, the red line shows that the subsidy must be larger and continue longer in order to redirect innovations. It will start at 0,129 and decrease until year 2030. If $A_{c0} = 0{,}5$, the subsidy must start at 0,144 and continue until year 2045. Figure 4b illustrates the redirecting cost. It shows the size of the subsidy in terms of total electricity production for the Environmental Concerned region.

Figure 5 shows how a subsidy can redirect innovations towards the clean sector for $A_{c0} = 0{,}8$. Initially when the expected profit is lower in the clean sector than in the dirty sector due to lower productivity, the government introduces a subsidy that makes the expected profit equal or larger in the clean sector. This subsidy is needed as long as the clean sector catches up with the productivity level in the dirty sector. When the productivity level in the clean sector is larger than in the dirty sector, the expected profit for the scientists will be larger in the clean sector even without a subsidy, so the subsidy is no longer needed.

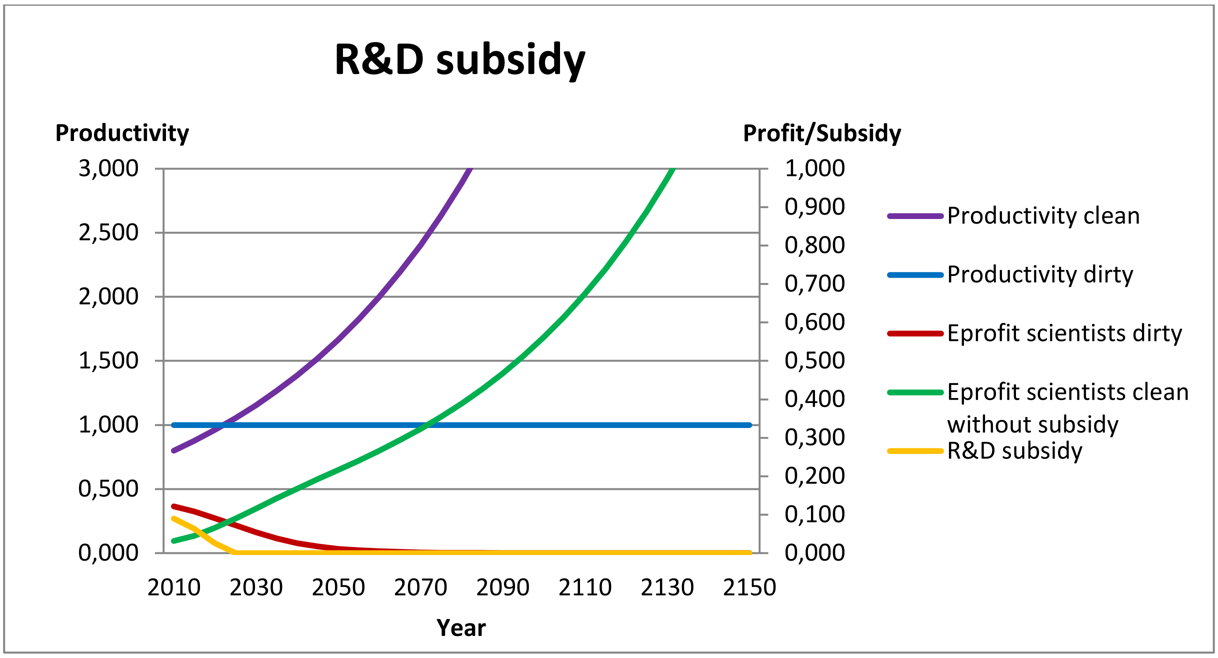

Figure 5: The subsidy is only needed until the productivity level in the clean sector catches up with the productivity level in the dirty sector.

If the government in Environmental Concerned choose to introduce a subsidy, an environmental disaster can be avoided. Figure 6 illustrates the economic situation for $A_{c0} = 0{,}8$ with the optimal subsidy given in figure 4a. If the subsidy is sufficiently high, the environmental quality will stabilize, and the discounted utility will increase as time goes by for both regions. Compared to the BAU situation in figure 3, the consumer in Environmental Concerned will be much better off, but the consumer in Unconcerned will be worse off since there will be a decrease in consumption compared to the BAU situation. The loss in utility for the Unconcerned consumer will be small compared to the gain for the Environmental Concerned consumer. The amount of consumption will otherwise be equal in the two regions.

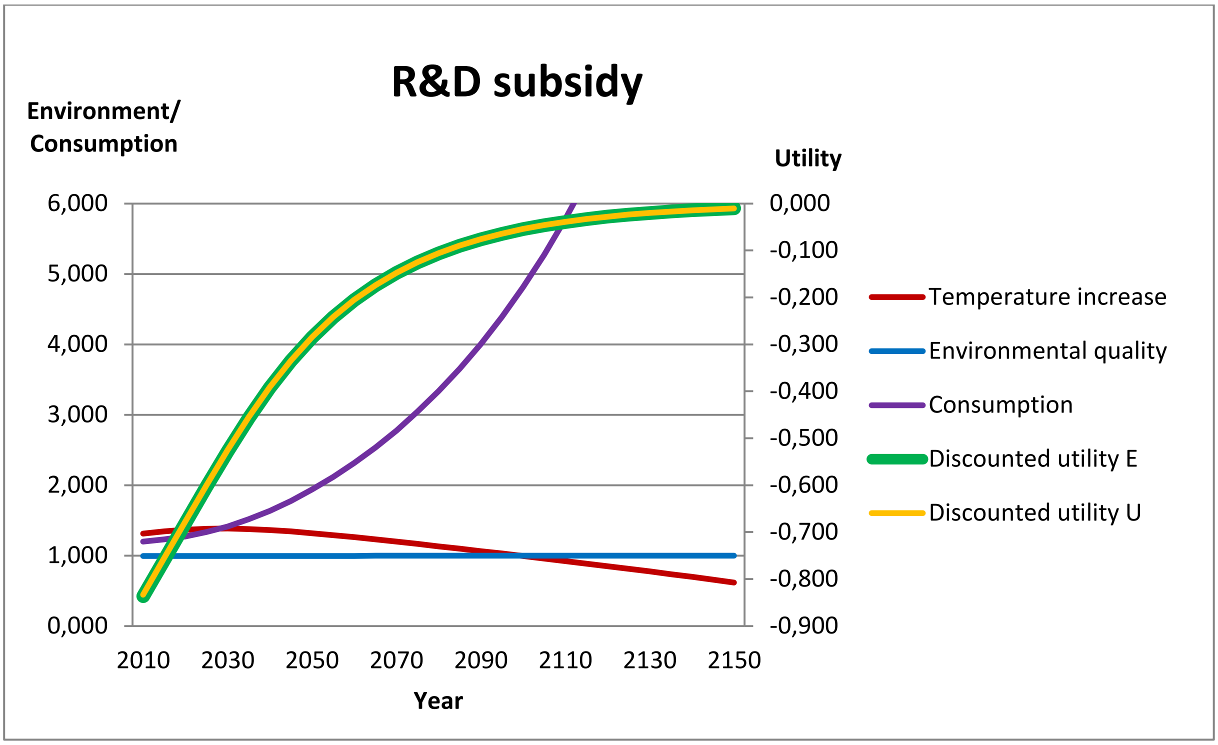

Figure 6: An environmental disaster can be avoided if the R&D subsidy is sufficiently high.

5.2.3 Carbon tax

Another policy instrument the government in the Environmental Concerned region can use in order to avoid an environmental disaster, is a carbon tax. Since the Unconcerned region thus not cares about the environment, it will not introduce a carbon tax. The government in Environmental Concerned must therefore consider if it has the possibility to redirect the innovations to the clean sector by using a carbon tax in its own region.

The key for the government in Environmental Concerned is to introduce a tax high enough, so that the scientists choose to direct their research towards the clean sector. As the productivity and activity in the clean sector catches up with the dirty sector, the emission tax is no longer needed. This is due to the same effects as in the subsidy case.

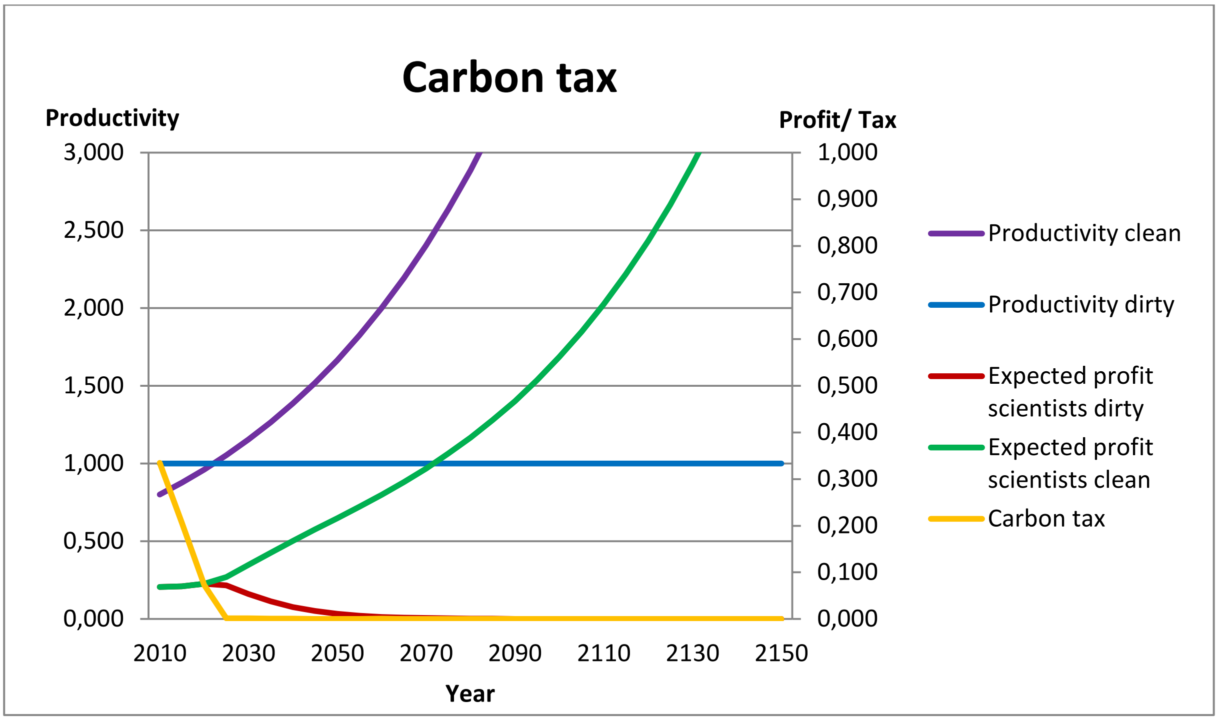

Figure 7: The innovations can be redirected towards the clean sector by introducing a carbon tax in the Environmental Concerned region.

Figure 7 illustrates how a carbon tax can switch the innovations from the dirty towards the clean sector by using a carbon tax when $A_{c0} = 0{,}8$. Initially the clean sector has lower productivity than the dirty sector. The government in Environmental Concerned can by using a carbon tax make the clean sector equally profitable for the scientists and therefore redirect the research. As the productivity in the clean sector catches up with the productivity in the dirty sector, the carbon tax moves towards zero. At this point the expected profit of a scientist in clean is larger than in dirty, so no scientist wants to redirect his/her research towards the dirty sector. The equilibrium condition is satisfied, so this corner solution with all scientists in the clean sector is stable.

If $A_{c0} = 0{,}65$ or $A_{c0} = 0{,}5$, the government cannot redirect the innovation by using a carbon tax alone. The highest possible productivity gap that makes it possible to solve the environmental problem with a tax alone, is $A_{c0} = 0{,}74$. This result is crucial and shows that the initial productivity gap between the two sectors determines which policy instruments that can be used in order to avoid an environmental disaster.

5.2.4 Optimal carbon tax when $A_{c0} = 0,65$ and $A_{c0} = 0,5$

In order to investigate the optimal taxation when $A_{c0} = 0{,}65$ and $A_{c0} = 0{,}5$, the model needs to be extended. In the numerical simulations I have change the periods from 28 to 38, so the model goes to the year of 2200 instead of 2150.

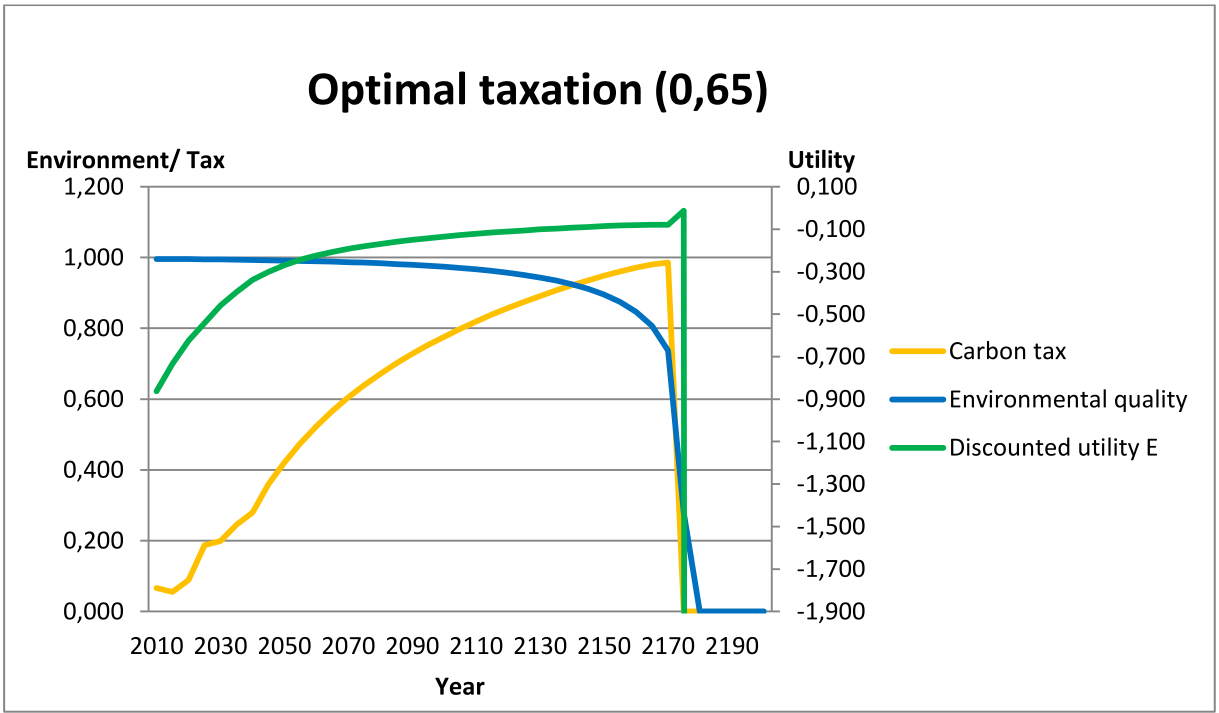

Figure 8: Optimal taxation policy for the Environmental Concerned region when $A_{c0} = 0{,}65$, and the government cannot redirect the innovations towards the clean sector.

Figure 8 highlight the optimal policy of the Environmental Concerned region when $A_{c0} = 0{,}65$. If taxation is the only available policy instrument, it is not possible for the government in Environmental Concerned to redirect innovations towards the clean sector when the productivity gap is of this size. The optimal policy will be an increasing carbon tax in order to delay an environmental disaster. When the environmental disaster occurs, the optimal carbon tax will be zero. A carbon tax will only be distortionary in this case, since the environmental quality will be zero no matter what.

In the BAU situation an environmental disaster takes place in the year 2150 in all the situations ($A_{c0} = 0{,}80$, $A_{c0} = 0{,}65$, $A_{c0} = 0{,}50$). When $A_{c0} = 0{,}65$, the government in Environmental Concerned can delay the disaster by introducing an increasing carbon tax as shown in figure 8. The disaster will then appear in year 2180 instead of 2150. If $A_{c0} = 0{,}50$, the government can delay the disaster until year 2175.

5.2.5 Optimal policy

Since the Unconcerned region has no policy instruments and does not care about the environment, the optimal policy will be from the perspective of the Environmental Concerned region. The government in Environmental Concerned maximizes the utility of their representative consumer using two policy instruments: A carbon tax and an R&D subsidy to clean research. In the optimal policy framework, the social planner in Environmental Concerned can combine these two policy instruments in order to achieve the best solution.

The optimal policy involves redirecting all the scientists towards the clean sector, since only then can an environmental disaster be avoided. It will be optimal for the social planner to move all the scientists in the first period compared to later. The reason for this is that the longer the scientists work in the dirty sector, the higher is the productivity gap between the two sectors. As the productivity in the clean sector catches up with productivity in the dirty sector, final output increases more slowly compared to the BAU situation. It will therefore be optimal to move the scientists in the first period in order to minimize the number of periods with slow growth in final output. This is the same result as in AABH.

In some situations it may be reasonable to believe that the subsidy can only be given to a fraction of the scientists. If the government in Environmental Concerned can only subsidise the scientists in its own region, the location of the scientist is crucial. If the majority of the scientists live in Environmental Concerned and therefore can be subsidised, an environmental disaster can be avoided. It will be optimal for the social planner to subsidise every scientist if that is possible. The more scientists that work in the clean sector, the sooner will the productivity in the clean sector be equal to the productivity in the dirty sector, and the subsidy will therefore be needed for a shorter time period. If the majority of the scientists live in Unconcerned, an environmental disaster cannot be avoided since the productivity in the dirty sector will always be greater compared to the clean.

The government in Environmental Concerned will use an R&D subsidy to clean research and a very small carbon tax in the optimal policy framework. AABH have shown that when $\varepsilon = 10$, the carbon tax is very low and applies only for a limited period. The reason for this is that the carbon tax should correct for the environmental externality from the dirty input, but since the switch to clean inputs happens almost immediately, this tax is unnecessary. This result also holds in the two regions framework. Since the optimal carbon tax is very low and only used for a limited period, there is not much difference between the subsidy case and the optimal policy situation.

Table 1 is an overview that compares the different utility levels for the different policies when $A_{c0} = 0{,}80$. The utility levels are the sum of the discounted utilities for the representative consumer in all time periods. Total subsidy is the sum of R&D subsidies needed to redirect the innovations towards the clean sector.

	BAU	Subsidy	Tax	Optimal
Utility E	− infinity	− 6,408	− 6,607	−6,408
Utility U	− 5,546	− 6,382	− 6,382	−6,382
Total Subsidy		0,179		0,174

Table 1: The utility levels and total subsidy needed to redirect innovations when $A_{c0} = 0{,}80$.

The utility level for the Environmental Concerned consumer will be equal in the subsidy and optimal policy case as discussed above. The only difference is that under the optimal policy, the subsidy needed to redirect the scientists will be a bit smaller. The utility will be higher when a subsidy is used compared to using a carbon tax, since using a carbon tax both to reduce emissions and to influence the direction of research, leads to excessive distortions as shown by AABH.

The consumer in Unconcerned will be worse off when the optimal policy is implemented compared to the BAU situation. The loss will however be much smaller than the gain of the

Environmental Concerned consumer, since that consumer's utility goes to minus infinity in the BAU situation.

5.3 Discussion

The numerical analysis above depends on several assumptions. In this section I will explain some of the assumptions I have made about the two regions framework and discuss what happens if they change. I will also discuss the research subsidy in the AABH model.

The two regions are of equal size in the framework above. If the Environmental Concerned region is largest, it will be easier to redirect the research since the market size effect from the Environmental Concerned region in equation (33) will be larger. Similar it will be harder and more costly in the opposite situation.

In the analysis I have used $\varepsilon = 10$, which indicates a high value of substitution between the two inputs. AABH also considers the situation when $\varepsilon = 3$. In this situation AABH finds that the subsidy needed to redirect innovations is larger and last longer, and that the optimal carbon tax will be increasing (See figure 1). It is therefore reasonable to believe that if $\varepsilon = 3$, it will be harder and more costly to redirect the research also in the two regions framework.

The Unconcerned consumer's utility function is independent of the environmental quality in the two regions framework. This assumption is based on countries different environmental concerns, and that some are located in areas that are more exposed to natural hazards. It is reasonable that the Unconcerned consumer will put some weight on the environmental quality as well, so this assumption is probably too strong. However, since the effect is relatively small compared to the other region, it is omitted for simplicity.

Earlier I assumed that the Unconcerned region will not try to affect the R&D decision. Since the consumer in Unconcerned will be worse off when the optimal policy is implemented (compared to the BAU situation), it is possible that the Unconcerned region starts subsidizing dirty R&D in order to neutralize the subsidy from Environmental Concerned. However the loss will be much smaller than the gain of the Environmental Concerned consumer, since that consumer’s utility goes to minus infinity in the BAU situation. It will therefore be possible for the Environmental Concerned region to compensate the Unconcerned consumer for staying out of the R&D decision, and this is the reason why the assumption is reasonable.

The research subsidy in AABH is financed through a lump-sum tax on the representative household. Since there is only one consumer who represents all workers, entrepreneurs and scientists, the consumer will both pay and receive the subsidy. The representative consumers utility is therefore not affected by the subsidy. In reality collecting taxes is hard and will probably cause some kind of costs and distortions.

6 Conclusion

This thesis investigates if it is possible to redirect R&D in a multi-region world where countries have different environmental concerns. In order to answer this question I have extended the AABH model into two regions that are identical in size and technology, the only difference is their environmental policy. I have looked at how the Environmental Concerned region can avoid an environmental disaster by introducing different policy instruments.

In order to avoid an environmental disaster, all the technology improvement must be redirected to the clean sector. The optimal policy involves redirecting every scientist to the clean sector immediately by the use of a subsidy for clean R&D together with a very small carbon tax.

It is reasonable to believe that in some situations the Environmental Concerned region cannot target all the scientists with a research subsidy. It will however still be possible to redirect the research if the Environmental Concerned region can subsidize a majority of the scientists. The process of redirecting technological change will take longer time and be more costly, but eventually all the research will be redirected to the clean sector, while the activity in the dirty sector will go to zero as time goes by.

If a research subsidy is not available, the scientist can be redirected to the clean sector by using only a carbon tax if the productivity gap between the two sectors is not too large. If $A_{d0} = 1$, the innovations can be redirected if $A_{c0} \geq 0{,}74$. This policy with an emission tax acting on its own is suboptimal to the case with the research subsidy, since it leads to excessive distortions.

The Kyoto Protocol has been criticized for not binding developing countries to any emission targets. Late 2015 a new climate conference is coming up in Paris, where the goal is to achieve a new international climate agreement involving every country in the world. This analysis shows that even if some countries choose not to contribute, it will still be possible to redirect R&D and avoid an environmental disaster if the Environmental Concerned countries go together and can target a majority of the scientists. This analysis also suggests that discussing emission targets might not be the way to go. What really needs to be done is to increase the research on clean technologies, so they can compete with and eventually surpass the dirty ones.

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Appendix

This is the mathematical framework used in the two regions case. The variables subscript $r \in \{E, U\}$ indicates the region. Since the innovation sector is global the quality of the machines A_{jit} and the machine price p_{jit} will be the same in both regions.

Production and innovation:

Final good:

(41) $$Y_{tr} = (Y_{ctr}{}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dtr}{}^{\frac{\varepsilon-1}{\varepsilon}})^{\frac{\varepsilon}{\varepsilon-1}},$$

(42) $$[p_{ctr}^{1-\varepsilon} + p_{dtr}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} = 1,$$

(43) $$\min_{Y_{ctr}, Y_{dtr}} \{p_{ctr}Y_{ctr} + p_{dtr}Y_{dtr}\}$$

given that $Y_{tr} = (Y_{ctr}{}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dtr}{}^{\frac{\varepsilon-1}{\varepsilon}})^{\frac{\varepsilon}{\varepsilon-1}},$

(44) $$\frac{p_{ctr}}{p_{dtr}} = \left(\frac{Y_{ctr}}{Y_{dtr}}\right)^{-\frac{1}{\varepsilon}}$$

Intermediates:

(45) $$Y_{jtr} = L_{jtr}{}^{1-\alpha} \int_0^1 A_{jit}{}^{1-\alpha} x_{jitr}{}^{\alpha}\, di,$$

(46) $$\max_{L_{jtr}, x_{jitr}} \left\{(p_{jtr} - \tau_{jtr})L_{jtr}{}^{1-\alpha} \int_0^1 A_{jit}{}^{1-\alpha} x_{jitr}{}^{\alpha}\, di - w_{tr}L_{jtr} - \int_0^1 p_{jit}\, x_{jitr}\, di\right\},$$

(47) $$x_{jitr} = \left(\frac{(p_{jtr}-\tau_{jtr})\alpha}{p_{jit}}\right)^{\frac{1}{1-\alpha}} L_{jtr}A_{jit}.$$

(48) $$L_{ctr} + L_{dtr} = \overline{L_r},$$

Machine producers:

(49) $$\max_{p_{jit}} \; \{p_{jit}x_{jitr}(p_{jit}) - \psi(1-s)x_{jitr}(p_{jit})\},$$

(50) $$p_{jit} = \frac{\psi\,(1-\text{s})}{\alpha},$$

(51) $$x_{jitr} = \left(\frac{(p_{jtr}-\tau_{jtr})}{(1-\text{s})}\right)^{\frac{1}{1-\alpha}} L_{jtr}A_{jit},$$

(52) $$\pi_{jitr} = (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jtr}-\tau_{jtr})^{\frac{1}{1-\alpha}}L_{jtr}A_{jit}.$$

(53) $$\begin{aligned}\pi_{jit} &= \pi_{jitE} + \pi_{jitU} \\ &= (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jtE}-\tau_{jtE})^{\frac{1}{1-\alpha}}L_{jtE}A_{jit} + (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jtU})^{\frac{1}{1-\alpha}}L_{jtU}A_{jit} \\ &= (1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}A_{jit}\left[(p_{jtE}-\tau_{jtE})^{\frac{1}{1-\alpha}}L_{jtE} + (p_{jtU})^{\frac{1}{1-\alpha}}L_{jtU}\right]\end{aligned}$$

Innovations:

(54) $$A_{jt} \equiv \int_0^1 A_{jit}\,di,$$

(55) $$A_{jt} = (1+\gamma\eta_j s_{jt})A_{jt-1},$$

(56) $$\Pi_{jtr} = \eta_j(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jtr} - \tau_{jtr})^{\frac{1}{1-\alpha}} L_{jtr} A_{jt-1}.$$

(57) $$\Pi_{jt} = \Pi_{jtE} + \Pi_{jtU} = \eta_j(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jtE} - \tau_{jtE})^{\frac{1}{1-\alpha}} L_{jtE} A_{jt-1}$$
$$+ \eta_j(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}}(p_{jtU})^{\frac{1}{1-\alpha}} L_{jtU} A_{jt-1}$$
$$= \eta_j(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} A_{jt-1}\left[(p_{jtE} - \tau_{jtE})^{\frac{1}{1-\alpha}} L_{jtE} + (p_{jtU})^{\frac{1}{1-\alpha}} L_{jtU}\right]$$

(58) $$\frac{\Pi_{ct}}{\Pi_{dt}} = \frac{\eta_c}{\eta_d} \times \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{direct\ productivity\ effect} \times$$
$$\left\{\left[\underbrace{\left(\frac{p_{ctE}}{p_{dtE} - \tau_{dtE}}\right)^{\frac{1}{1-\alpha}}}_{price\ effect\ Environmental\ C} \times \underbrace{\frac{L_{ctE}}{L_{dtE}}}_{market\ size\ effect\ Environmental\ C}\right] + \left[\underbrace{\left(\frac{p_{ctU}}{p_{dtU}}\right)^{\frac{1}{1-\alpha}}}_{price\ effect\ Unconcerned} \times \underbrace{\frac{L_{ctU}}{L_{dtU}}}_{market\ size\ effect\ Unconcerned}\right]\right\}$$

(59) $$s_{ct} + s_{dt} \leq 1,$$

With a subsidy from Environmental Concerned:

(60) $$\Pi_{ct} = \eta_c(1+\gamma)(1-\alpha)\alpha^{\frac{1-2\alpha}{1-\alpha}} A_{ct-1}\left[(1+q_{tE})(p_{ctE})^{\frac{1}{1-\alpha}} L_{ctE} + (p_{ctU})^{\frac{1}{1-\alpha}} L_{ctU}\right]$$

Consumption and the environment:

(61) $$C_{tr} = Y_{tr} - \psi\left(\int_0^1 x_{citr}\, di + \int_0^1 x_{ditr}\, di\right),$$

Environmental Concerned:

(62) $$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \; u_E(C_{tE}, S_t),$$

(63) $$lim_{C\downarrow 0} \frac{\partial u(C,S)}{\partial C} = \; \infty, \quad lim_{S\downarrow 0} \frac{\partial u(C,S)}{\partial S} = \; \infty, \quad lim_{S\downarrow 0}\, u(C, S) = -\infty,$$

(64) $$\frac{\partial u(C,\overline{S})}{\partial S} = 0,$$

Unconcerned:

(65) $$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \; u_U(C_{tU}),$$

Global pollution:

(66) $$S_{t+1} = -\xi(Y_{dtE} + Y_{dtU}) + (1+\delta)S_t,$$