Is low carbon taxation optimal climate policy for a developing country?

A numerical simulation of technology adoption

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Abstract

The United Nations Framework Convention on Climate Change (UNFCCC) stated in 1992 that developed countries should take the lead in combating the adverse effects of climate change, contributing more to global emission reductions than developing countries. To reduce their burden, and differentiate climate responsibilities between industrialized and developing countries, low carbon taxes in developing countries have been suggested (Rosendahl, 2004, Kverndokk et al., (2014). However, there is little knowledge about the effects of low carbon taxation in developing countries. Is low carbon taxation optimal climate policy or could this in fact lead to a disadvantage instead?

The aim of this thesis is to explore the role of carbon taxes in developing countries in four different scenarios, where the time frame for the global investment in clean technology is altered. The analyses are based on the model of Environment and Directed Technical Change, developed by Acemoglu et al. (2012). The global framework in their model is adapted to the national level of a developing country, and the innovation sector in the initial model is replaced with a "learning by doing-effect".

The results of the numerical analysis suggest that given that, if a global shift from dirty to clean technology will take place within the next 50 years and that the substitutability between the clean and the dirty input factors is high, it would be optimal for a small developing country to deviate from the classic "policy ramp" of emission tax policy. Instead of letting the tax increase at the rate of the permit price, the optimal trend of the emission tax should be bell-shaped and excessively higher than the permit price, until the use of clean technology starts to accelerate. If the conditions of early technology shift and high substitutability are in place, the implementation of the UNFCCC principles of "common but differentiated responsibilities" should not include reduced carbon taxation in developing countries. A temporarily increased emission tax instead, will contribute to making the clean technology competitive, and opening possibilities for increased growth and consumption in the long run.

Preface

This thesis completes two years master studies in economics at the University of Oslo. I would like to thank my supervisor, Mads Greaker, for turning the last semester of my studies into the most rewarding of all. His genuine interest, boundless knowledge and ability to inspire have been invaluable. My co-supervisor Karine Nyborg deserves great thanks for guiding a confused student in the right direction, turning frustration to motivation.

I would also like to thank the Oslo Centre for Research on Environmentally friendly Energy (CREE) for granting me a student scholarship, and for providing an inspiring environment during the time of writing.

The warmest thanks go to my parents for their never-ending support and belief in me, and special thanks to my father for numerous discussions and believing in this thesis, when I did not.

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Maiken Katrine Weidle

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Content

1 Introduction

“There is still time to avoid the worst impacts of climate change, if we take strong action now”. These are the opening remarks of the Stern Review: The Economics of Climate Change (2007). The consciousness and knowledge about climate change is growing, much due to an increase in the attention of research in this field. Since the foundation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, there has been a steady increasing literature on growth, resources and environment.

The most important recent contribution in this area is the Fifth Assessment Report on Climate Change, compiled by the Intergovernmental Panel on Climate Change (IPCC), published in spring 2014. The report provides a clear and the most up-to-date view of the state of scientific knowledge relevant to climate change. It consists of three Working Group reports and a Synthesis Report which integrates and summarizes the main conclusions in the other reports. The objective of the Working Group III report was to compile options for mitigating climate change and their underlying technological, economic and institutional requirements (IPCC 2014).

In a comment on the report, three of the scientific contributors, Fuglestvedt, Hertwich and Kverndokk (2014) emphasized the paradox which arose during the previous decade: At the same time as a variety of climate policies were implemented, global emissions increased. This paradox resulted from the fact that climate policy in the 2000`s was focused on high income countries. These policies did not target reduction of the coal based industrialization in middle income countries which was the greatest single contributor to increasing emissions over the last 10 years. However, Fuglestvedt et al. described this development not only as negative; it has brought many people out of poverty in a short time. On the other hand, this raises the difficult question as to who is to bear the heaviest burden of emission reductions. In contrast to earlier reports, the IPCC (2014) report strongly emphasizes questions of justice and fairness in the analysis of climate change policies.

One positive trend shown in the results of the report is that growth in global emissions seems to level out. The bad news, however, is that this is not nearly sufficient if the UN target of a maximum 2 °C global warming is to be reached. The report takes the reader through different possibilities of reduced emissions. The common factor of all suggestions is that it will be costly, and that the costs will increase the longer we wait. Electricity production without burning oil, coal, gas or firewood is highlighted as one of the most important measures that can be taken at this point. The international society has to switch to renewable energy or nuclear energy, a process which will accelerate if the subsidies of fossil fuels are reduced. Investments in infrastructure which do not bind us to emission intensive technology are particularly important at this time of extensive global urbanization (IPCC, 2014).

The topic of equity and fairness has, as mentioned, received increased attention in the Fifth Assessment Report. Which principles should the allocation of emission abatements be based on? Should all countries contribute equally? Or should the countries affected the most, abate the most? A third option of responsibility distribution is that the countries which have polluted the most historically also should abate the most. The list of potential principle regimes is long. There is, however, a growing consensus that a global problem must be met with a global solution and therefore all countries should participate (Stern, 2007). The international community agreed on the Kyoto Protocol already in 1998, where Article 10 states, that there are “common but differentiated responsibilities”. The United Nations Framework Conventions on Climate Change (UNFCCC) communicate even clearer, that developed countries should contribute more to global emission reductions than developing countries. UNFCCC Article 3.1 and 3.2 state the following:

> *”1. The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.*
>
> *2. The specific needs and special circumstances of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change, and of those Parties, especially developing country Parties, that would have to bear a disproportionate or abnormal burden under the Convention, should be given full consideration.” (UNFCCC 1992: Article 3.1-3.2)*

The question which arises from this starting point is *how* the UN goal of differentiated responsibilities could be achieved? How should the developing countries contribute? Should they be spared from paying the price of other countries’ misconducts and if so, in which way? Which policies are optimal for a developing economy? The Clean Development Mechanism

(CDM)[1], included in the Kyoto Protocol is already in place. Many academic contributions have also tried to answer these questions. Suggestions of low carbon taxation, increased emission caps or no participation at all in climate agreements are among the proposed solutions for developing countries (Rosendahl, 2004, Kverndokk et al., 2014). However the question arising from these proposals, is whether releasing the developing countries from their responsibility is in fact doing them a disservice? Could it be that developing countries which are discharged from their abatement responsibilities, consequently are withheld an opportunity to acquire knowhow of clean technology? Will this lack of knowledge impair their ability to apply new technologies, and consequently stay as poor in the future as in the past? If investments in clean technology on a global level are increasing, could it be optimal for a developing country to join the industrialized countries and participate in a switch to clean technology?

The policy question at hand is thus the following: What is the optimal policy for a small developing country in scenarios with different global investments in clean technology? Will it be optimal to speed up the use of clean technology for example by imposing a higher emission tax on dirty technology? Is there a danger that developing countries will lag behind industrialized countries “for ever”, if they do not take part in the use of new technologies? Will it be too expensive or welfare reducing if they do?

Acemoglu, Aghion, Bursztyn and Hemous (2012) have developed a model of directed technical change, hereafter referred to as AABH model. This is an endogenous growth model which includes an innovation sector where research is divided between “clean” and “dirty” technologies, respectively. Increasing research and development (R&D) in clean technology, will lead to an increase in productivity and profitability of the clean technology. In the model, the consumer`s utility depends on both consumption and environmental quality. Use of dirty technology results in environmental degradation, and if the global carbon stock increases beyond a given threshold, environmental disasters will happen. The AABH model focuses on which policies can prevent such environmental disasters.

The main message of the AABH model is that interventions to tackle climate changes do not have to hurt long run economic growth. If the clean and dirty intermediates in production are substitutes, and if R&D on dirty technologies is brought to a halt and all R&D efforts are

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[1] CDM is defined in Article 12 in the Kyoto Protocol. It allows countries to earn reduction credits through implementation of emission reduction projects in developing countries. See http://cdm.unfccc.int/index.html

transferred to clean technologies, the long run economic growth will not be reduced. In contrast to classical economic theory, Acemoglu et al. conclude that it is in fact very costly to implement these policies by an emission tax alone. Their results show that subsidies to R&D in clean technology should be used to catalyze research efforts from dirty to clean technology.

The AABH model is modified in a discussion paper by Greaker and Heggedal (2012). The authors question the patent solution of the original model, and hence provide an extended version with long lived patents replacing the one-period patents in the original model. They show that the new patent solution reestablishes the role of the carbon tax, and that the role of the research subsidies becomes far less crucial.

In this thesis I will apply the AABH global model of directed technical change, and adopt it to the conditions of a small developing economy. This will be done by the following adaptations: (1) Technological development happens outside the developing country, e.g. is exogenous. (2) However, the country can affect the speed of its own adoption of the technologies. That is, it cannot just take the technology and utilize it whenever it wants: it has to learn to use it first. The R&D sector in the global model is thus replaced with a “learning by doing-effect”, where the developing country acquires knowledge through the utilization of clean technology.

I will further extend the local framework to include a climate agreement which contains a national cap on emissions and an international permit price. Using the AABH model and the Greaker and Heggedal (2012) simulations, I will provide a numerical analysis of the optimal taxation and the use of clean versus dirty technology in the developing country. I will evaluate four different scenarios of global R&D investment. Scenario 1 is defined by a starting point where research and investment in clean technology never happens. Scenarios 2-4 show a research shift from dirty to clean technology after 100 years, 50 years or 5 years, respectively. These scenarios correspond to the emission scenarios depicted in the Special Report on Emission Scenarios (SRES) published by IPCC (2000). All numerical analysis will be conducted in Microsoft Excel 2010.

As expected, the numerical analysis shows, that in the cases of no global investment in clean technology at all, or no investment during the first 100 years, utilization of clean technology in production will not enhance welfare in the developing country. Given such a low global level of clean technology, the developing country cannot improve the level of knowledge of the new technology through increased utilization. Without this “learning by doing- effect” it will be too expensive for the developing country to switch to clean technology. In the other scenarios with a global technology shift from dirty to clean technology after 50 or 5 years respectively, the pattern is quite different. Now the learning by doing-effect is strong enough for the developing country to benefit from the global research conducted in industrialized countries, and a shift to clean technology will then be the optimal policy.

2 Literature review

Given the large and growing literature on resource and environmental economics, I will in this section outline both the main contributions which the AABH model is based on and later modifications of the model. Since UNFCCC was established in 1992, more and more research on the impacts of climate change has become available. Today regularly published, international reports such as the *Assessment Reports* of the Intergovernmental Panel on Climate Change (IPCC), the *World Energy Outlook* from the International Energy Agency (IEA) and the *Environmental Outlook* by OECD are the most utilized sources of climate change information. In addition, two contributions led by researchers, instead of institutions, have been quite influential over the last decade.

The first contribution, the *Stern Review: The Economics of Climate Change* (Stern, 2007), was produced on request of the British Prime Minister and Chancellor of the Exchequer. The task to establish a foundation for political decisions concerning the effects of climate change on the world economy, had been assigned to former chief economist and senior vice president of the World Bank, Sir Nicholas Stern. He and his team were to compile a report containing the economics of moving to a global low-carbon economy, the potential in different approaches to an adaptation to climate changes, and specific lessons for the UK (Stern 2007). The result was an over 500 pages long report which argued very strongly that damages from climate changes are large, and that nations must undertake sharp and immediate reductions in greenhouse gas emissions. The Stern Review was fervently debated see for example Byatt et al. (2006), Dasgupta (2006), Weitzman (2007) or Nordhaus (2007). Despite the critique, the report remains a benchmark for research on climate change economics.

The other contribution was the pioneering work of William Nordhaus (1994), Sterling Professor of Economics at Yale University. He proposed an integrated assessment model of climate change and the economy, the Dynamic Integrated Climate Economy model (DICE model). Later contributions include among others the Regional Integrated Climate Economy model (RICE model), an updated and applied approach to his DICE model (Nordhaus, 2008) and a critical evaluation of the Stern Review (Nordhaus, 2007). One main critique from Nordhaus`s point of view was Stern`s low discount rate. Nordhaus argued that the near-zero discount rate used in the Stern Review was not consistent with today`s market real interest rates and saving rates. Nordhaus showed that the conclusions of the Stern Review did not hold if a higher discount rate was applied. This is the background for the different discount rates used in the numerical example described by Acemoglu et al. (2012). Their results supported the importance of choosing an appropriate level of discount rate.

An important modification of the AABH model was described in the previously mentioned paper by Greaker and Heggedal (2012). They added long lived patents to the AABH framework, and showed that this change in the patent structure reduces the essential role of research subsidies and reestablishes the role of the carbon tax. A thorough description of economic theory concerning optimal carbon taxes and the principals of a market for tradable emission permits is given in the textbook by Perman et al. (2011). Greaker et al. (2013) highlighted the concept of a global greenhouse gas (GHG) budget and showed what this would mean in terms of emission reductions. Rosendahl (2004) analyzed the implications of induced technical change for environmental policy. He concludes that industrialized countries should have higher emission taxes than developing countries because technology development happens in the former countries. Kverndokk et al. (2014) arrive at the same conclusion based on equity principles. None of these contributions look at technology adoption, and acknowledges that this also may be a learning process.

The AABH model is chosen for this analysis because the framework contains technical adoption and distinguishes between investment in dirty and clean technology. This distinction is important because a country can be quite familiar with the old technology, but have no knowledge of the new one. This difference could have policy implications. As the AABH model is used for the analysis, I will in the next chapter review the parts of the model which are relevant to this thesis.

3 Theoretical Framework

3.1 The environment and directed technical change

The AABH model is a framework which allows a study of the responses of different technologies due to changes in environmental policies. It is a global framework which applies the whole world as one unit of analysis. There is one final good in this global economy, and it is produced using two intermediate input factors; clean and dirty (Y_{ct} and Y_{dt}). These two intermediates are produced by labour and dirty or clean specific machines. In the context of this model, dirty, respectively clean machines equal dirty, respectively clean technologies. This is of course not an accurate description of reality. Considering equipment that uses electrical power, a particular machine could be both dirty and clean at the same time, depending on which input was used in production. However, this simplification will not congest the effects the authors want to analyze.

The two types of technologies can be defined in several ways. In the paper of Acemoglu et al. (2012) no definition of clean and dirty technology is provided. In this thesis, I will therefore use the definitions of Greaker and Heggedal (2012). They define the group of dirty technologies as technologies for oil- , coal- and gas extraction, internal-combustion engines and power derived from coal and gas. Clean technologies, on the other hand, are defined as renewable energies, hydrogen- or electrical cars and new ways to organize electricity markets to make access to renewable energy easier.

Use of dirty input factors causes environmental degradation. It is not given from which part of the production this degradation originates. One can argue that the problem is caused by the technology of the machines, the input factors or extraction of the dirty resources. The source of degradation could for instance be the *production* of the input factor, for example production of electrical power using coal. It could also be the *use* of the input factor, such as coal used in steam boats. A third option is the *extraction* of the dirty input factor, for example extraction of oil sand or crude oil from a rainforest. Degradation can also result from petroleum refineries who are large polluters (Heede 2014). This thesis is based on the assumption that the use of dirty input factors in production of the final good will lead to environmental degradation, without distinguishing between the different sources mentioned above. If the quality of the environment falls below a critical threshold, an environmental disaster occurs, and consumer utility falls to negative infinity. In their paper, Acemoglu et al. (2012) use this model to shed light on which policies can prevent such an environmental disaster.

3.2 General framework of the AABH model

The AABH (2012) model depicts an infinite horizon, discrete time, global economy. There is a continuum of households, and a representative household has utility from a final consumption good, C_t, and environmental quality, S_t. Utility is given by

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

Acemoglu et al. assume that when S_t reaches a level of "maximum environmental quality", given as the quality of the environment absent from any human pollution, $\bar{S}$, the marginal increase in environmental quality is small, hence

$$(2)\quad \frac{\delta u(C, \bar{S})}{\delta S} = 0$$

A unique final good is produced competitively using clean and dirty input factors, Y_c and Y_d, according to an aggregate production function

$$(3)\quad Y_t = \left(Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

where Y_t is the final good and ε is the elasticity of substitution between the two sectors. Acemoglu et al. assume that a dirty sector corresponds to the production of the dirty input factor and a clean sector corresponds to the production of the clean input factor. If $\varepsilon > 1$, the two sectors are gross substitutes, if $\varepsilon < 1$, they are gross compliments.

The price of the final good results from the input prices p_{ct} and p_{dt} where the relative price of the clean input factor, compared to the dirty input factor, is decreasing in relative supply. The price of the final good is normalized to one so that

$$(4)\quad \left[p_{ct}^{1-\varepsilon}+p_{dt}^{1-\varepsilon}\right]^{\frac{1}{\varepsilon-1}}=1$$

Production

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

$$(5)\quad Y_{jt}=L_{jt}^{1-\alpha}\int_0^1 A_{jit}^{1-\alpha}x_{jit}^{\alpha}di$$

where $j\in\{c,d\}$ and $\alpha\in(0,1)$, L_{jt} is labour in each sector, A_{jit} is productivity of the machine of type i used in sector j at time t, and x_{jit} is input of machine type i.

The input firm´s problem, as shown in Greaker and Heggdal (2012), is:

$$(6)\quad \max_{L_{jt},x_{jit}}\left\{(p_{jt}-\tau_{jt})L_{jt}^{1-\alpha}\int_0^1 A_{jit}^{1-\alpha}x_{jit}^{\alpha}di-w_tL_{jt}-\int_0^1 p_{jit}x_{jit}di\right\}$$

where τ_{dt} is the carbon tax $(\tau_{ct}=0)$ and p_{jit} is the price of machine type i in sector $j\in\{c,d\}$. From the first order conditions, the demand for machine type i can be written as

$$(7)\quad x_{jit}=\left(\frac{(p_{jt}-\tau_{jt})\alpha}{p_{jit}}\right)^{\frac{1}{1-\alpha}}L_{jt}A_{jit}$$

The market clearing condition for labour demand requires that a worker is either employed in the dirty or in the clean sector and that total labour demand is less than or equal to total labour supply which is normalized to one:

$$(8)\quad L_{ct}+L_{dt}\le 1$$

Machines for both sectors are supplied by monopolistically competitive firms. Regardless of the quality of the machines and of the sector for which it is designed, producing one unit of any machine costs ψ units of the final good. The firm which supplies the machines is profit maximizing. As will be shown in the next section, a successful scientist obtains a one-period monopoly for his new technology and becomes the entrepreneur for one period. The supply firm´s problem can thus be written as

$$(9)\ \max_{p_{jit}} \left\{ \left(p_{jit} - \psi \right) \frac{\left(p_{jt} - \tau_{jt} \right) \alpha}{p_{jit}} L_{jt} A_{jt} \right\}$$

From (9) the value of an innovation as a function of $\psi, \tau_{jt}, \alpha, L_{jt}$ and A_{jt} is obtained. Lastly the market clearing condition for the final good implies

$$(10)\ C_t = Y_t - \psi \left(\int_0^1 x_{cit} di + \int_0^1 x_{dit} di \right)$$

Innovation

The machines have different productivity, and the productivity can be increased by conducting R&D. Average productivity in each sector is defined as

$$(11)\ A_{jt} \equiv \int_0^1 A_{jit} di$$

This implies that A_{dt} corresponds to the average productivity for dirty technology and A_{ct} is the average productivity for clean technology.

At the beginning of every period each scientist decides whether to direct his or her research to clean or dirty technology. He or she is then randomly allocated to at most one machine, and each machine is also allocated to at most one scientist. s_{jt} represents the number of scientists employed in each sector. Innovation is successful with probability $\eta_j \in (0,1)$ in sector $j \in \{c, d\}$ and the invention increases the quality of a machine by a factor $1+\gamma$ ($\gamma > 0$). A successful scientist who has invented a better version of a machine obtains a one-period patent and becomes the entrepreneur for the current period of production of machine i. He or she obtains a monopoly, and can thus earn profit in one period, given by equation (9). A new invention increases the productivity of machine i from A_{jit} to $(1+\gamma)A_{jit}$. Average productivity evolves over time according to

$$(12)\quad A_{jt} = \left(1+\gamma\eta_j s_{jt}\right)A_{jt-1}$$

Average productivity today, is a result of the average productivity in that sector the previous period, multiplied by the probability of successful innovations, the number of scientists doing research in that sector and the factor for productivity increase with a successful innovation. An implicit assumption made here, is that the potential for technological development is equal in both sectors.

To single out which effects that drive the choice between clean and dirty R&D, the relative profitability of research must be characterized. Acemoglu et al. start with an expression for expected profits $\prod_{jt}$ of a scientist doing research in sector j;

$$(13)\quad \prod_{jt} = \eta_j(1+\gamma)(1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt} A_{jt-1}$$

The expected profits of a scientist engaged in research in sector j is composed of the probability of successful innovation, η_j, the machine´s quality increase from the innovation, $(1+\gamma)$, and the profit from having a monopoly on an old machine in one period, $(1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt} A_{jt-1}$. This last part of equation (13) is the solution to the maximization problem in equation (9).

The relative benefit from undertaking research in the clean sector relative to the dirty sector, is consequently given by the ratio

$$(14)\quad \frac{\prod_{ct}}{\prod_{dt}} = \frac{\eta_c}{\eta_d} \times \underbrace{\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}}_{\text{price effect}} \times \underbrace{\frac{L_{ct}}{L_{dt}}}_{\text{market size effect}} \times \underbrace{\frac{A_{ct-1}}{A_{dt-1}}}_{\text{direct productivity effect}}$$

This ratio describes the direction of technical change, which is determined by the average productivity in the two sectors. The higher the ratio, the more profitable it is to direct R&D to clean technologies. Acemoglu et al. highlight three forces relevant to the movements of innovation. They distinguish between the price effect, market size effect and the direct productivity effect. The incentives to innovate in clean versus dirty sector machines are shaped by these. I will return to these effects in section 3.2.1.

The market clearing condition for scientists requires that the number of researchers employed either in the clean sector, s_{ct}, or in the dirty sector, s_{dt}, is less or equal to total demand which is normalized to one:

$$(15) \quad s_{ct} + s_{dt} \leq 1$$

In the AABH framework it is assumed that the allocation is always a corner solution where all researchers either enter the clean or the dirty sector. Hence $s_{dt} = 1$ and $s_{ct} = 0$, or vice versa.

The environment

Finally there is the environmental quality S_t which depends on a stock pollutant, environmental degradation and regeneration. In the interval $(0, \bar{S})$ it evolves over time according to

$$(16) \quad S_{t+1} = -\xi Y_{dt} + (1+\delta) S_t$$

where the parameter ξ measures the rate of environmental degradation resulting from production of the dirty inputs. δ is the rate of environmental regeneration which measures how much pollution the nature is able to neutralize. If the right hand side of the equation is negative, $S_{t+1} = 0$, there is an environmental disaster. Since $\bar{S}$ is the maximally attainable environmental quality corresponding to zero pollution, $S_{t+1} = \bar{S}$ if the right hand side of the equation is greater than $\bar{S}$.

Equation (16) captures several important features of environmental changes in practice. First that greater degradation typically lowers the regeneration capacity of the globe. For example the more rainforest that is depleted, the less carbon it can contain, and this contributes to further global warming. Second the upper bound $\bar{S}$ captures the idea that degradation comes from pollution and that pollution cannot be negative. Third the relation encapsulates the possibility that the environmental quality may deteriorate to a point of no return, resulting in an environmental disaster which cannot be reversed.

3.2.1 Laissez-faire allocation

Within this framework two possible equilibria are analyzed. First a situation where there is no policy intervention and the government does nothing to influence the outcome, a so-called laissez-faire equilibrium. Second a situation where a social planner maximizes total welfare. I will start by going through the laissez-faire equilibrium. Acemoglu et al. make the assumption that the clean sector is initially sufficiently backwards compared to the dirty sector. This means that in a laissez-faire situation innovation starts in the dirty sector. Acemoglu et al. distinguish between three effects which drive innovation. These are depicted in equation (14) as the direct productivity effect, the market size effect and the price effect.

The direct productivity effect pushes innovation towards the sector with the highest initial productivity. Productivity growth in absolute terms is higher in that sector. Each researcher is more productive in a sector with more research knowledge, and hence profit maximizing researchers are driven to the sector with the highest productivity in the current period. This effect is often referred to as the “building on the shoulders of giants-effect” because of the similarity in mechanisms. One reaches higher by building on the shoulders of giants as opposed to starting on the ground. In the same way productivity growth is higher in absolute terms in the sector with higher initial productivity, e.g. $A_{dt} > A_{ct}$.

The market size effect directs innovation towards the sector with greater employment and consequently the greater market for machines, e.g. $L_{dt} > L_{ct}$. The scientist can make more profits from his or her innovation if the technology is demanded by a greater market. Given that the two inputs are substitutes, the sector with the larger employment is also the sector with the higher aggregate productivity. This means that the market size effect and the direct productivity effect always push innovation towards the same technology.

The price effect directs innovation towards the sector with the highest price on inputs. If the price on the clean input is higher relative to the price on the dirty input, it is more profitable to do research on clean technology. A higher input price implies more gains to be made by increasing the efficiency of the input factor. The high price also indicates less supply and less access of the input factor, meaning there is more profit to be made by using that input factor efficiently.

Which of these effects that dominate, is determined by the elasticity of substitution between the two sectors, and the relative levels of development of the two technologies. Acemoglu et al. (2012) conclude that in a laissez-faire equilibrium innovation will favor the more advanced sector which, given their assumption, is the dirty sector. Consequently a laissez-faire equilibrium involves all researchers allocating to the dirty sector with the consequence that all research will be carried out on dirty technology. Innovation starting in the dirty technology also increases the gap between the dirty and the clean sector and the initial pattern of the equilibrium is reinforced. Only the productivity in the dirty sector, A_{dt}, grows, while productivity in the clean sector, A_{ct}, remains constant. As a consequence, only a long run growth rate for the dirty input factor is present.

The laissez-faire equilibrium always leads to an environmental disaster. This follows directly from the fact that dirty production always grows without bounds, meaning that no constraints are binding. A level of production greater than $(1+\delta)\xi^{-1}\overline{S}$ necessarily leads to a disaster in the next period. To avoid this kind of disaster the government can subsidize scientists to work in the clean sector, using a proportional profit subsidy financed through a lump sum tax on the representative household. Denoting this subsidy rate by q_t, they get this new expression for the expected profit from research in the clean sector:

$$(17)\quad \Pi_{ct} = (1+q_t)\eta_c(1+\gamma)(1-\alpha)\alpha\, p_{ct}^{\frac{1}{1-\alpha}} L_{ct} A_{ct-1}$$

This implies that a sufficiently high subsidy on clean research can redirect innovation towards the clean sector and consequently avoid environmental disaster.

3.2.2 Socially optimal allocation

The socially optimal allocation is a dynamic path of final goods production, consumption, input production, machine production, labour allocations, scientist allocations, environmental quality and qualities of machines which maximizes the intertemporal utility of the representative consumer in equation (1), subject to the constraints of equation (3), (5), (8), (10), (12) (15) and (16). The social planner´s problem is hence

$$(18)\ \max_{Y_{dt},s_{dt}} \left\{ \begin{array}{l} \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t,S_t) - \lambda_1 \left(Y_t - \left(Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \right) - \lambda_2 \left(Y_{ct} - L_{ct}^{1-\alpha} \int_0^1 A_{cit}^{1-\alpha} x_{cit}^{\alpha} di \right) \\ -\lambda_3 \left(Y_{dt} - L_{dt}^{1-\alpha} \int_0^1 A_{dit}^{1-\alpha} x_{dit}^{\alpha} di \right) - \lambda_4 \left(L_{ct} + L_{dt} - 1 \right) - \lambda_5 \left(C_t - Y_t - \psi \left(\int_0^1 x_{cit} + \int_0^1 x_{dit} di \right) \right) \\ -\lambda_6 \left(s_{ct} + s_{dt} - 1 \right) - \lambda_7 \left(A_{ct} - (1+\gamma\eta_c s_{ct}) A_{ct-1} \right) - \lambda_8 \left(A_{dt} - (1+\gamma\eta_d s_{dt}) A_{dt-1} \right) \\ -\lambda_9 \left(S_{t+1} + \xi Y_{dt} - (1+\delta) S_t \right) \end{array} \right\}$$

A key conclusion is that an optimal policy must use both a carbon tax and a subsidy for clean research. The former is applied to control carbon emissions, the latter to influence the path of future research. Relying on a carbon tax alone would be excessively distortionary. Both the tax and the subsidy are redistributed and financed lump sum.

This social optimal allocation must correct for three relevant market failures in the economy. First is the underutilization of machines due to monopoly pricing in the laissez-faire equilibrium. This is corrected by a subsidy for machines. Second the environmental externality is corrected by introducing a wedge between the marginal product of the dirty input factor in production of the final good and the price. This wedge corresponds to a tax τ_t on the use of the dirty input factor and is referred to as a carbon tax. The tax reflects that in optimum the marginal cost of reducing production of the dirty input by one unit, equals the marginal benefit from higher environmental quality in all subsequent periods. Third, the socially optimal allocation also internalizes the knowledge externality for innovation, and allocates scientists to the sector with the higher social gain from innovation.

In the AABH framework both a carbon tax and a subsidy for clean research are necessary to implement the social optimum. The subsidy deals with future environmental externalities by directing innovation towards the clean sector. The carbon tax targets the current environmental externality more directly, by reducing production of the dirty input factor today.

An optimal policy requires avoiding disaster because an environmental disaster means that the consumers have utility of negative infinity. When the discount rate is sufficiently low, the optimal allocation implies positive long run growth. A correctly chosen subsidy for clean research ensures that innovation only occurs in the clean sector. When productivity in the clean sector is sufficiently higher than productivity in the dirty sector, innovation in the clean sector will have become profitable enough for the subsidy to be superfluous. The economy will then generate a long run growth rate equal to the growth rate of productivity in the clean sector, $A_{ct} = \gamma\eta_c$. Production of the dirty input factor also decreases to zero over time, and consequently the environmental stock, S_t, reaches $\overline{S}$ in finite time because of positive regeneration. This further ensures that the optimal carbon tax will reach zero in finite time.

Comparing the laissez-faire allocation with the social optimal allocation, it is clear that without directed technical change, the allocation of scientists is insensitive to other policies. In such a case redirecting innovation to the clean sector is not possible. The optimal environmental regulation must then prevent an environmental disaster by imposing ever-increasing carbon taxes. But with the directed technical change, optimal environmental regulation can be achieved using temporary taxes and subsidies, with little cost in terms of long run distortions and reduced long run growth.

3.2.3 Quantitative example

Acemoglu et al. provide a quantitative example to highlight the effects of different values of the discount rate and elasticity of substitution on optimal environmental regulation. One period is chosen to correspond to 5 years. They set $\eta_c = \eta_d = 0,02$ and $\gamma = 1$ so that the long-run annual growth rate equals 2 %. They further take $\alpha = 1/3$ such that the share of national income spent on machines is approximately equal to the share of capital.

An estimation of the global elasticity of substitution is not part of their paper, but they assume that values for ε should be quite high. They consider two values for ε; a low value of $\varepsilon = 3$ and a high value of $\varepsilon = 10$. Contrasting these two allows them to highlight the crucial role of the elasticity of substitution in determining the optimal policy.

To relate the atmospheric concentration of carbon to the environmental quality variable, S_t, they use a common approximation to the relationship between the increase in temperature since preindustrial times (in degrees Celsius), Δ, and the atmospheric concentration of carbon dioxide (CO_2 in ppm).

$$(19)\ \Delta = 3\log_2(C_{CO_2}/280)$$

This relation implies that a doubling of atmospheric concentration in CO_2 leads to a 3°C increase in current temperature (IPCC 2007). Disaster is defined as a temperature increase equal to $\Delta_{disaster} = 6^{\circ}$C (Stern 2007).

Furthermore Acemoglu et al. estimate the parameter ξ, from the observed value of Y_d and the annual emission of CO_2, and choose δ such that only half of the amount of emitted carbon contributes to increasing CO_2 concentration in the atmosphere, the rest being offset by environmental regeneration (IPCC 2007).

Next they parameterize the utility function as

$$(20)\ u(C_t, S_t) = \frac{(\phi(S_t)C_t)^{1-\sigma}}{1-\sigma}$$

Acemoglu et al. base their choice of parameters and discount rates on the contributions of Stern (2007) and Nordhaus (2007) as discussed in chapter 2. They set $\sigma = 2$ which matches Nordhaus´ choice of intertemporal elasticity of substitution. This utility function contains the term $\phi(S)$, which captures the cost of environmental quality degradation. The function for this is chosen as

$$(21)\ \phi(S) = \varphi(\Delta(S)) \equiv \frac{\left(\Delta_{disaster} - \Delta(S)\right)^{\lambda} - \lambda\Delta_{disaster}^{\lambda-1}(\Delta_{disaster} - \Delta(S))}{(1-\lambda)\Delta_{disaster}^{\lambda-1}}$$

Matching this function with Nordhaus´ damage function over the range of temperature increases up to 3°C, leads to a value of $\lambda = 0{,}1443$. In the AABH simulations Acemoglu et al. consider both the Stern discount rate of $\rho = 0{,}001$ per annum and the Nordhaus discount rate of $\rho = 0{,}015$ per annum.

They show a subsidy of the clean sector, allocation of scientists to the clean technologies, the carbon tax, the share of clean inputs in total production and the increase in temperature in the socially optimal allocation for the following configurations: $[\varepsilon = 10, \rho = 0{,}015]$,

$[\varepsilon = 3, \rho = 0,015]$ and $[\varepsilon = 3, \rho = 0,001]$. The configuration $[\varepsilon = 10, \rho = 0,001]$ gives the same results as $[\varepsilon = 10, \rho = 0,015]$ and is therefore left out. This illustrates the fact that when the elasticity of substitution is sufficiently high, the discount rate is of little importance.

Subsidy: When the discount rate is low, ρ = $0,001$, regardless of which level of elasticity of substitution, the optimal policy involves an immediate shift of all research to clean technologies. With $\varepsilon = 3$ and $\rho = 0,015$, the switch to clean research occurs around year 50, and the optimal subsidy of clean research is temporary. When $\varepsilon = 10$, the subsidy is lower and of shorter duration than with the lower elasticity of substitution. This is because the initial gap between clean and dirty technologies is smaller in this case. The lower the elasticity of substitution is, the larger the optimal subsidy and the longer the transition period.

Carbon tax: If $\varepsilon = 10$ carbon taxation is low and necessary only for a limited period because the rapid switch to clean inputs makes this tax unnecessary. When $\varepsilon = 3$ and $\rho = 0,015$ however, the shift to clean technology is delayed, and a much higher and increasing carbon tax is needed.

Input production: When $\varepsilon = 10$, the clean sector takes over most of input production quite rapidly. It takes only 30 years for 90 % of the input factor to switch to the clean sector. In contrast, when $\varepsilon = 3$ and $\rho = 0,001$, even though the switch to clean research is immediate, it takes over 100 years before 90 % of the input factors are supplied using clean technology.

Temperature: Finally when $\varepsilon = 10$, there is a small increase followed by a decrease in temperature. The pattern is similar, though the increase and the following decline are prolonged when $[\varepsilon = 10, \rho = 0,001]$. If $\varepsilon = 3$ and $\rho = 0,015$, temperatures increase for 300 years before reaching a maximum, fairly close to the disaster level. In general the results show that if the elasticity of substitution between clean and dirty inputs is sufficiently high, then which discount rate one uses has little influence on the optimal environmental policy.

4 Country level model

4.1 Model description

In the AABH model the whole world is analyzed as one unit. I will in this section apply the global framework to one small developing country, interpreting it as a local framework. In this process some adaptions of the original framework must be made.

Learning by doing

The first adaptation is the assumption that there is no R&D in the developing country. Consequently the innovation sector in the global model is not present in the country level model. This assumption is supported by, among others, Rosendahl (2004) and Coe et al. (1997) who state that almost all R&D activity in the global economy is concentrated in industrialized countries. The small developing country can therefore not influence global research and technology investment. Global productivity and productivity growth of dirty and clean technologies cannot be affected by the small developing country`s actions. Consequently these variables are not determined in the country level model. The global productivity frontier for clean and dirty technologies, A_{jt}^{G}, are exogenous values.

Despite the fact that there is no R&D in the developing country, knowledge of new technology can still be attained. This can be done in several ways, for example through foreign trade, other forms of interaction with industrialized countries or through learning by doing. The learning by doing-effect is the mechanism where productivity grows due to increased utilization of technology, and I assume that this effect is present in the developing economy. Thompson explains that “Numerous empirical studies of productivity growth have shown a tendency for productivity to rise with cumulative output, particularly at early stages of production. [..] [E]conomists most often refer to this as the learning curve or learning by doing” (Thomson 2001:103). Rosendal (2004) argues that in addition to R&D, learning by doing is the most important source of induced technological change.

The developing country is therefore always able to acquire some knowledge of new technology, but learning by doing increases the pace. In the context of the country level model, this means that local productivity, A_{jt}^{L}, can increase despite lack of domestic R&D.

Local productivity increases faster if a learning by doing-effect is present. The more clean technology is used in production, the more efficient it becomes, and the faster it approaches the global research front.

An implicit assumption inherent in the learning by doing theory is that a form of technology transfer between the developing and industrialized country has to be present. Coe et al. (1997) conclude that R&D spillovers from industrialized countries in the north to less developed countries in the south are substantial. Stephan Alberth (2008) shows that experience is the superior explanatory variable in forecasting technology trends, and Thompson (2001) further conveys that the most common measure of experience is cumulative output.

In his text book «*Næringsstruktur og utenrikshandel*» (1993), Victor Normann discusses the product cycle theory, originally introduced by Raymond Vernon. The base of his theory is that products can either be produced in an industrialized country or in a developing country. The industrialized country can easily manufacture new products, while the developing country has low productivity in new products and relatively high productivity for more mature products. He derives equations for price- and labour terms which determine the development pace and turnover of products from industrialized to developing countries. The price relation is an increasing function of the product turnover, and approaches one as the turnover rate increases (Normann 1993:155-158). This mechanism of the price relation with product turnover from industrialized to developing countries, is parallel to the mechanism of technology spillovers from industrialized to developing countries. The technology adoption equation in the country level model is therefore based on the theories outlined in this literature.

I define the local productivity equation as

$$(22)\quad A_{jt+1}^{L} = A_{jt}^{L} + T_{jt}\left(A_{jt}^{G} - A_{jt}^{L}\right)$$

where $j \in \{c, d\}$. A_{jt}^{L} and A_{jt}^{G} are the local and global productivity levels, respectively. T_{jt} is the speed of technology adoption where $T_{jt} \in (0,1)$. Productivity of clean, respectively dirty technology in the small country is a function of the local productivity at time t, and the distance between the local productivity level and the global frontier for the given technology. The higher the value of T_{jt}, the faster the developing country adopts the new technology. If

$T_{jt} = 0$, there is no productivity growth in the developing economy. In the very long run, $A^L_{jt+1} = A^G_{jt+1}$ if A^G_{jt+1} stays constant. As already mentioned I capture that T_{jt} is not exogenous, but depends on the level of experience. Technology adoption is defined as

$$(23)\quad T_{jt} = \mu\left(1 - \frac{1}{\sum_0^t Y_{jt}^{\theta}}\right)$$

where $j \in \{c, d\}$, $\theta > 0$ and the technology transfer rate is $\mu \in (0,1)$. The technology adoption equation is an increasing function of accumulated utilization of the respective technology which approaches μ. The higher μ, the faster is the learning process in the developing country. θ is another expression of the effect of increased utilization of the technology. The higher θ, the faster is the technology adoption.

The assumption from the general framework regarding clean technology still holds. Clean technology is relatively backwards compared to dirty technology, and hence has a lower productivity at time t than dirty technology. Consequently, productivity of the clean technology will not change unless global investments in clean technology increase. Considering today`s level of technology in the petrol- and gas industry versus for example solar power, this assumption seems reasonable.

Energy

I add the assumption that the developing country produces its own energy, and that this energy is produced with clean or dirty technology. Here I introduce a simplification of the global framework, and view the final consumption good, Y_t, as energy. Consumption of the other goods in this macro production function grows at a constant rate, proportional to energy. Energy enters all sectors of society, and energy consumption is positively correlated with general consumption (Lee 2005). Due to this I can measure consumption in terms of energy. There is no import or export of energy, consequently total energy consumption is limited by what the country is able to produce itself. The developing country trades in other commodities with industrialized countries, otherwise the technology transfer would be quite limited. My interpretation of the AABH macro production function in equation (5) is therefore

$$(24)\quad Y_t = A_t L_t^{1-\beta_1-\beta_2} K_t^{\beta_1} E_t^{\beta_2}$$

where $\beta_1, \beta_2 \in (0,1)$, E_t is energy and $A_t L_t^{1-\beta_1-\beta_2} K_t^{\beta_1}$ is exogenously given and normalized to one. Energy can, as in the general framework, be produced by clean and dirty input factors. I thus interpret the relation for the final consumption good, equation (3) in the general framework as

$$(25)\quad E_t = \left(Y_{ct}^{\frac{\varepsilon-1}{\varepsilon}} + Y_{dt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}$$

I further assume that the developing country is too small for its production and emissions to significantly affect the global carbon stock and environmental quality. As it has no influence on the global investment in clean and dirty technology, it follows from the first assumption that the levels of the carbon stock and environmental quality are exogenous values in the country level model.

International climate agreement

Up to this point I have developed a baseline for the country level model. In this baseline however, the developing country has no incentives to reduce emissions. Its actions cannot affect the global carbon stock. If there is no local effect on environmental quality, there are no incentives for emission abatements. If the small developing country would enter an international climate agreement, however, this would change. The country is still too small for its emissions to have an effect on the global level, but given that the climate agreement is binding, the developing country then has incentives to reduce emissions. I assume that the small, developing country is committed to a binding international climate agreement.

The climate agreement contains a cap-and-trade system with a total allowable quantity of permits, the global cap, and a system for trade with emission permits. Marketable permit systems are based on the principle that an increase in emissions at one location must be offset by an equivalent decrease in emissions somewhere else. A limit is set on the total quantity of emissions, but the regulators do not attempt to determine how the total allowed quantity is allocated between participating agents. The total amount of emission permits is then initially allocated between the participants of the agreement. If a country wants to emit more than the assigned amount, it has to buy additional emission permits in the market. If the country emits less than the assigned amount, it can sell the remaining permits in the market. These are the standard mechanisms of a market with tradable permits (Perman et al., 2011). In addition to these standard mechanisms, I assume the permits are initially allocated by a control authority and that the national emission cap for the small, developing country is set equal to its local emissions in period 0.

For a cap-and-trade system to function optimally the following conditions must hold: First the climate agreement is binding, and hence no country can pollute more than the national cap without buying additional emission permits. A monitoring- and penalty system is in place to eliminate all incentives to shirk. There is also a guarantee that emission permits can freely be traded between countries at whichever price is agreed upon for that trade (Perman et al., 2011).

The mechanism for establishing the equilibrium permit price is elegantly described by Perman et al. Consider a firm or a country which is assigned a certain amount of emission permits.

"Some firms hold more permits than the quantity of their desired emissions [..]. The value of a marginal permit to these firms is zero. Others hold permits in quantities insufficient for the emission that they would have chosen in the absence of the permit system. The marginal valuation of permits to these firms will depend upon their emission abatement costs. Some will have high marginal abatement costs, and so are willing to pay high prices to purchase emission permits. Others can abate cheaply, so that they are willing to pay only small sums to purchase permits; their marginal permit valuation is low." (Perman et al., 2011: 205)

In this situation some firms will try to buy additional permits, while others will try to sell from their initial holding. Firms which have fewer initial emission permits than they desire can choose between buying additional permits and reducing their emissions. Based on the available supply and demand, a market equilibrium permit price will be established. Perman et al. (2011) further explain that if the total quantity of permits issued is identical to the level of emissions which would emerge from an emission tax at the rate π^*, then a marketable permit scheme will generate an equilibrium permit price π^*. In effect the marketable permit system is hence an equivalent instrument to emission taxes. Consequently, I expect an optimal emission tax in the country level model to follow the path of the international permit price.

The optimal path of the emission tax is also increasing over time. Traditional microeconomic theory conveys the insight that in optimum the marginal cost equals the marginal benefit. The same principle holds for emission. In optimum marginal abatement costs should every year equal the marginal benefit from the reduced emissions. Since emissions increase over time, the marginal benefit of abatement does too. Consequently efficient emission reductions follow an increasing path. This is known as a "policy ramp", with low emission reductions in the short run, and increasing emission abatements in the medium and long run (Nordhaus 2008).

Model constraints

Acemoglu et al. (2012) discuss the possibility of the two input factors being both substitutes and compliments. They conclude that it is hard to find an empirically relevant case for the two input factors being complements, and state that the case of substitutes appears as the more relevant benchmark. Based on these statements, I will in this thesis always assume that the input factors are substitutes, $\varepsilon > 1$ and not consider the case where they are compliments. Thinking of the two input factors as clean and dirty electrical power, they are practically perfect substitutes. If the two input factors were compliments the outcome of the analysis would be quite different, but due to the reasons mentioned, this possibility is not discussed.

A second extension discussed by Acemoglu et al. is whether to include exhaustible resources. By extending the general framework, one could easily analyze an economy with an exhaustible resource by including an extra term in the equation for production of the dirty input factor. If however the global amount of this particular resource is so large that there will be environmental disaster before the scarcity constraint kicks in, adding the exhaustible resource will not affect the outcome of the model. In World Economic Outlook 2012, published by the International Energy Agency (IEA), calculations about global resources are presented. The report states that "No more than one-third of proven reserves of fossil fuels can be consumed prior to 2050 if the world is to achieve the 2 °C goal, unless carbon capture and storage (CCS) technology is widely deployed" (IEA 2012:4). Based on these results I assume that there is too much of the exhaustible resources for the scarcity constraint to kick in. I will thus not add exhaustible resources in the analysis of the country level model.

4.2 IPCC technology path scenarios

In the country level model the values for global investment in clean technology are exogenous. Estimates for global technology growth in dirty and clean technologies are provided by IPCC. In a Special Report *Emissions Scenarios* (2000), different scenarios for global technology investment in the near future are calculated.

The report establishes that different social, economic and technological developments have a strong impact on emission trends, without assuming explicit climate policy interventions. It further covers a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The report reinforces the results of earlier reports which conclude that the main driving forces of future greenhouse gas trajectories will continue to be demographic change, social and economic development and the rate and direction of technical change. Policies that explicitly address climate change are consequently excluded for the scenarios to be a valid base for any policy. The scenarios are an appropriate tool for analyzing how driving forces may influence future emission outcomes (IPCC 2000).

The report shows 40 different scenarios derived from four qualitative storylines. These story lines yield four sets of scenarios called families. I will use family A1 with three subgroups characterizing alternative developments in energy technologies, keeping the other driving forces constant. Group 1 is fossil fuel intensive, group 2 is balanced and group 3 is predominantly non-fossil fuel.

> *"The A1 story line and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and a rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B)." (IPCC, 2000: 2)*

In the numerical analysis the fossil intensive A1F1-scenario, will correspond to a shift in global R&D from dirty to clean technology after 100 years. Similarly the balance across all sources A1B-scenario will correspond to a shift to clean R&D after 50 years and the non-fossil energy source A1T-scenario will correspond to a shift after 5 years.

5 Numerical example

5.1 Numerical model description

In this section I will provide a numerical analysis of the country level model. The simulations will show the optimal path of the emission tax, and the use of clean and dirty input factors in the developing country, given the different scenarios of global investment in clean technology.

I use the Acemoglu et al. (2012) model and the Greaker and Heggedal (2012) simulations to obtain the global values for research and investment in the two types of technology. Using their numerical example, I shift technology research from dirty to clean technology in period 20, period 10 and period 1, respectively. From these simulations I get the exogenous values for the global research frontier in clean and dirty technologies and the global carbon stock for each scenario. I put these exogenous values into the country level numerical model.

Firstly I construct a baseline case which corresponds to the baseline of the Greaker and Heggedal (2012) simulations without the innovation sector. The baseline case is then extended to include the international climate agreement with the national cap on emissions and an international permit price. The cap on emissions is set equal to the level of the dirty input factor in period 0, $Y_{d0} = 0,695$. The initial international permit price is calibrated to match the relation between the price on emission permits in the European Union Emission Trading System (EU ETS), GDP and GHG emissions for the European Union in 2011, according to

$$(26) \qquad \frac{\text{GHG emissions } x \text{ Permit price}}{\text{GDP } x \text{ Energy share}}$$

Eurostat (2014) provides absolute numbers for total GHG emissions in CO_2 equivalents and GDP. Consumer energy expenditure as share of GDP in the European Union in 2011 was 10 % (Enerdata 2014), and the ETS permit price was € 10 in September 2011. Applying this ratio to the model values gives an initial permit price of 0,05. From this starting point, it grows by 4 % per period. The growth rate is supported by Greaker et al. (2013), and increases by a yearly rate equal to the risk adjusted real interest rate.

I introduce four scenarios for global investments in clean technology; a shift to clean technology never occurs, a shift to clean technology takes place in period 20, period 10 or period 1, respectively. These periods corresponds to a shift in technology after 100 years, after 50 years and after 5 years, respectively. The scenarios correspond, as discussed in the previous section, to the scenarios in the IPCC Special Report on Emission Scenarios (2000). Accumulated dirty and clean input factors equal 1 in period 0. The software is programmed to maximize the sum of discounted utilities, given the constraints that factor prices and the emission tax are nonnegative.

Concerning the parameters, I use the same calibrations as Acemoglu et al. (2012) for the parameters calibrated in their model. As described in section 2.2.3, these are the capital share $\alpha = 1/3$, the elasticity of substitution $\varepsilon = 10$, the discount factor $\rho = 0{,}015$, $\sigma = 2$ and $\lambda = 0{,}1443$. The high elasticity case is chosen because of the assumption about clean electrical power and dirty electrical power being highly substitutable. Based on the critique of the Stern discount factor, I only apply the Nordhaus discount factor (Nordhaus 2007). One period corresponds to five years, and the model runs for 40 periods. The technology transfer parameter is set to $\mu = 0{,}5$, based on the contribution by Coe et al. (1995) on north south spillovers. From equation (23) the parameter $\theta = 1$ and will hence have no influence on the results. In section 5.3 I will conduct several sensitivity analyses for this parameter.

5.2 Results

Baseline case

In the baseline case with no international climate agreement, the temperature increases beyond the critical threshold. Environmental quality approaches zero in the year 2150, and at the same time summarized discounted utility drops to negative infinity. The carbon tax in this case is zero, because the small country cannot do anything to affect the current situation. It is therefore optimal to consume as much as possible before a disaster happens. These results show the same picture as the baseline in the Greaker and Heggedal (2012) simulations.

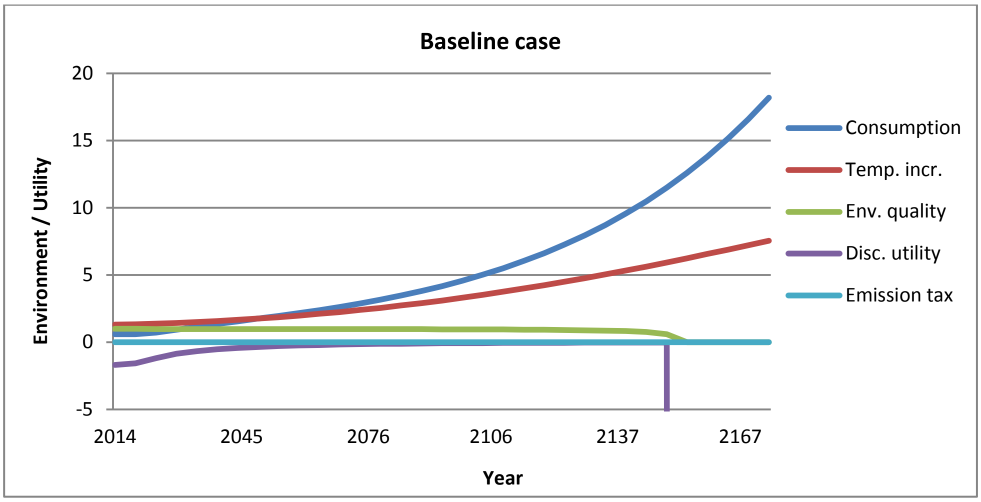


Figure 1: The baseline case shows development in environmental quality, consumption and utility when there is no global switch in technology and the developing country does not participate in a climate agreement.

Case 1: No switch in technology research

In case 1, I introduce the international climate agreement with a national cap on emissions and an international permit price. In this first scenario there is, however, no global shift from dirty to clean technology. Despite this lack of change in technological investments, I assume that the global community, due to the international climate agreement, is somehow able to stop the dangerous development before an environmental disaster occurs. This assumption alone leads to stagnation in the temperature increase and environmental quality just before the critical level is reached. Summarized discounted utility consequently does not drop to negative infinity as in the baseline case, but is rather continuously increasing. The same holds for consumption. See figure A1 in the appendix.

It is optimal with an emission tax on the dirty input which increases at the rate of the international permit price, 4 % per period. As previously described, a country can choose between reducing emissions by abating more, or emitting more whilst buying additional emission permits to compensate. If marginal abatement costs are higher than the permit price, it is cheaper to buy additional permits in the market. If the marginal abatement costs are lower, gains can be made by abating more and selling the remaining permits. Consequently in optimum, the national marginal abatement cost equals the international permit price. If this is to be attained, the only possible solution is to set the emission tax equal to the permit price.

Thus in a benchmark case consistent with economic theory (Perman et al., 2011), the emission tax will increase with the rate of the price on the tradable permits. This is the pattern depicted in the results of this first case.

The use of dirty input factors is continuously increasing in this scenario. It is a reflection of the global research frontier where there is no research on clean technology. Due to this fact, the use of clean input factors is initially at a very low level, and finally decreases to zero after 50 years. When there is no global shift to clean technology, there is no benefit from shifting to clean technology by increasing the learning by doing-effect for the developing country. Thus the use of clean technology never passes the use of dirty technology in the developing country, despite the carbon tax levied on dirty technology.

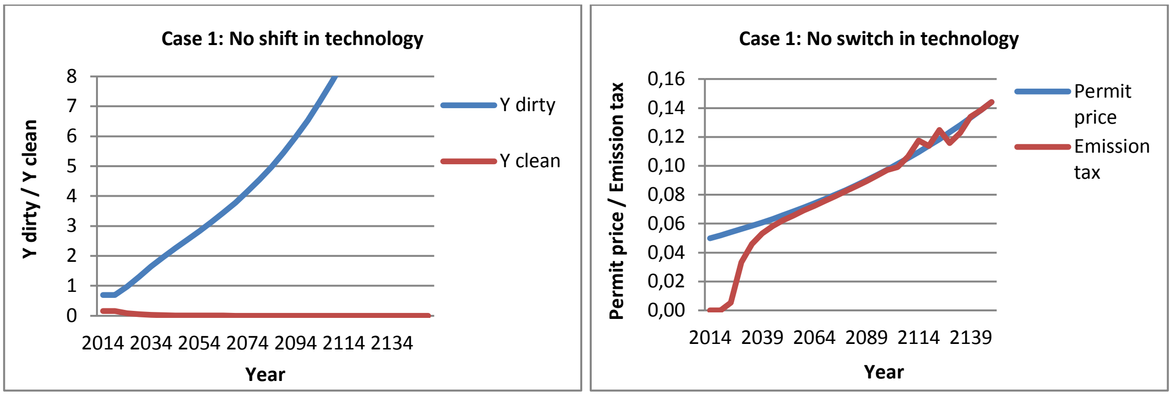


Figure 2: The use of dirty and clean input factors and the emission tax path when there is no switch to clean technology.

Case 2: Switch of technology research after 100 years

In the second case I introduce a global switch in technology research after 100 years, where all research and investments shift from dirty to clean technology. I keep the assumption that the world manages to stagnate growth in the carbon stock before the critical threshold. Hence the pattern from the first case continuous. The temperature increase is still positive, but both the temperature increase and environmental quality stagnates just before the critical threshold. Discounted utility is continuously increasing. Consumption, however, has a slightly different pattern. Instead of being continuously increasing, it reaches a maximum five periods after the switch and decreases from that point onwards. The change in technology takes place too late in time for the clean technology to become productive. At the same time the switch reduces profitability of the dirty technology such that production stagnates. As a consequence there is a reduction in consumption. See figure A2 in the appendix. The sensitivity analysis will later show that this reduction is temporary. The time horizon of the original simulations is not long enough to capture the point where use of the clean technology passes use of the dirty, and production and consumption increases again. This development is depicted when the number of model periods is increased from 40 to 50.

The pattern of the emission tax does not change significantly. The emission tax path follows the growth of the international permit price. It is, however, less smooth than in the first scenario. This results from lack of precision in the model. The simulations are not accurate enough for the path to be exact, but the irregularities are of no relevance. A counterfactual scenario shows that if the emission tax was pegged to the permit price, the results in this scenario would not change. Utilization of the dirty input factor stagnates at the time of the switch, as previously discussed. The model does not contain enough periods for the clean technology to catch up, thus the use of the clean input factor, which goes to zero after 50 years, remains unchanged. One can however in period 33 see that the use of the clean input factor starts to rise again, and the sensitivity analysis shows that if the number of model periods is increased to 50, the use of the clean input factor increases. The model is however kept at 40 periods because it is difficult to solve for more periods in all cases. Giving predictions about outcomes in 200 years is also in general quite problematic due to potentially unknown variables. The further into the future the predictions go, the higher is the probability of omitted variables and for these reasons as well the time frame is kept at 200 years.

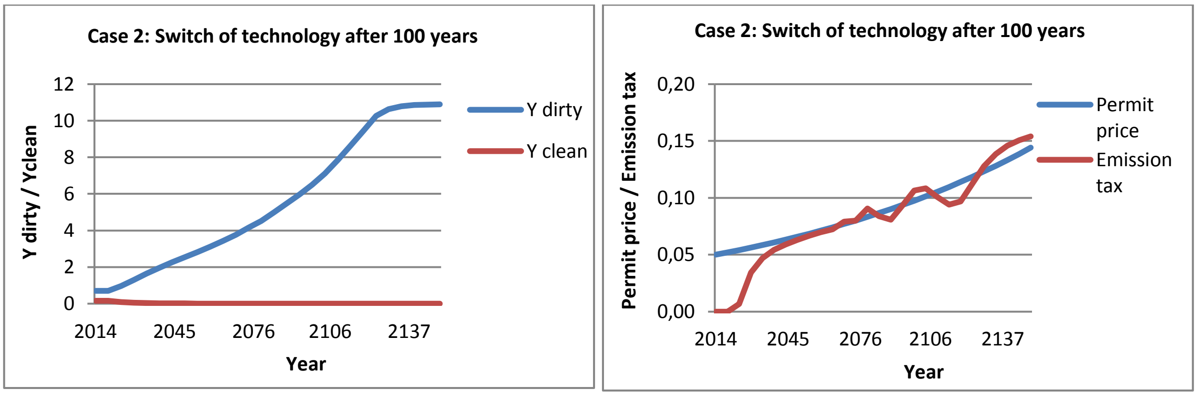


Figure 3: The use of dirty and clean input factors and the emission tax path when the technology switch takes place after 100 years.

Case 3: Switch of technology research after 50 years

In the third case the global switch takes place after 50 years. There is a gradual temperature increase, but it never passes 3,5°C. Environmental quality therefore remains constant through all the time periods in this scenario. Summarized discounted utility is continuously increasing, and somewhat higher than in the previous case. Consumption follows a concave path until period 25 when it increases rapidly. This results from a reduction in the emission tax, and drastic increase in the use of clean input which leads to increased total production in the country. As consumption is measured in terms of energy consumption, and the country is a closed economy how energy is concerned, increased production therefore results in increased consumption. See figure A3 in the appendix.

In this scenario the patterns of the emission tax and the clean input factor change quite dramatically. The emission tax no longer follows the global permit price. Instead it increases rapidly and peaks three periods after the switch. It then turns and decreases to the level of the permit price. From that point the emission tax follows the growth of the permit price onwards. The simulations show an optimal emission tax which is increasing as long as the use of the dirty input factor is increasing, resulting in a bell shaped emission tax path in that time frame. The increased tax reduces profitability of the dirty technology relative to the clean in the periods before the clean technology becomes competitive. It also keeps the price of the clean input factor lower than in a counterfactual scenario. The more the clean input factor is used, the greater is the learning by doing-effect, and consequently the switch to clean technology can occur sooner. Sensitivity analysis later show that the bell shaped emission tax pattern strongly depends on the elasticity of substitution being high, $\varepsilon = 10$.

When there is full information about an approaching technology switch, optimal policy for the developing country is to speed up the use of clean technology to increase the learning effect. Learning is a positive externality in this framework. All economic agents except the government are myopic in the AABH model, and thus do not take this externality into account. The government can internalize the externality by imposing the high emission tax, stimulating increased utilization of the clean technology. Through restraining the use of dirty technology, and increasing utilization of the clean, the developing country can faster acquire knowledge of the new technology. Consequently the gap between the domestic productivity and the global frontier of clean technology is not as great as it otherwise would have been. A result of the accelerated technology switch is that the use of the dirty input factor only increases for 100 years, before it drops and approaches zero at the end of the simulations. Utilization of the clean technology remains almost constant at a level just above zero, before it after 110 years accelerates and increases continuously.

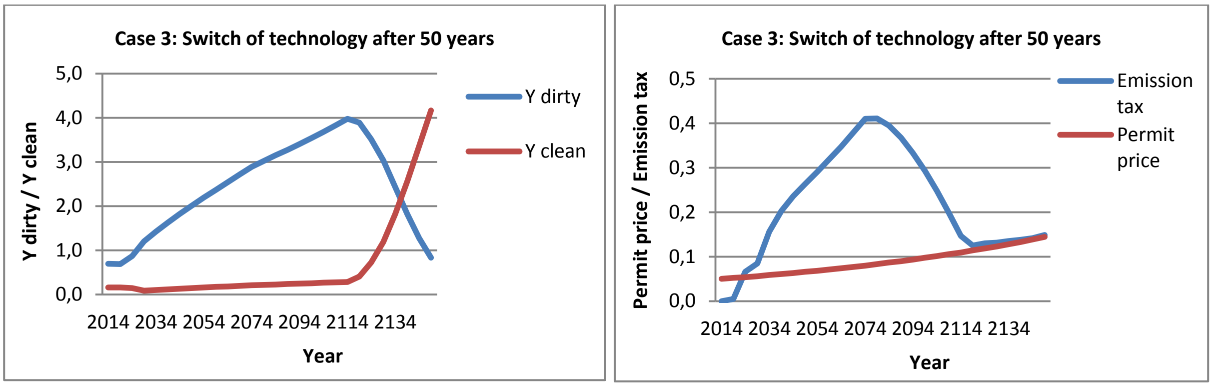


Figure 4: The use of dirty and clean input factors and the emission tax path when the technology switch takes place after 50 years.

Case 4: Switch of technology research after 5 years

In the fourth and last case, the global technology switch takes place after 5 years. Discounted utility and consumption are continuously increasing as expected. The temperature increase is gradually declining and consequently environmental quality is constant at the same level as in the previous case. See figure A4 in the appendix. These results are similar to the ones in the previous scenario.

The bell shaped pattern of the emission tax in the third case, continues in the fourth. The difference is that peak of the emission tax happens at an earlier point in time, and that the maximum level is lower than in the third case. The emission tax accelerates from the point of the switch, reaches a maximum after 10 years, and then drops to zero after 55 years. The drop to zero happens at the exact same time as the use of the dirty technology equals zero. When there is no use of the technology which causes the emissions, there is no need for a positive emission tax either. It would, however, make no difference if the emission tax were to increase at the rate of the permit price in this scenario as well. There would be no real effects. Use of the dirty input factor decreases almost continuously before it approaches zero after 60 years. Use of the clean input factor is rapidly and continuously increasing from period one, due to the early switch to clean technology. The pattern and the intuition is the same here as in the third case. An emission tax restrains the use of the dirty input factor, and an emission tax which is higher than the permit price contributes to a reduction of the relative price of the clean input factor, which additionally stimulates the use of the clean input factor.

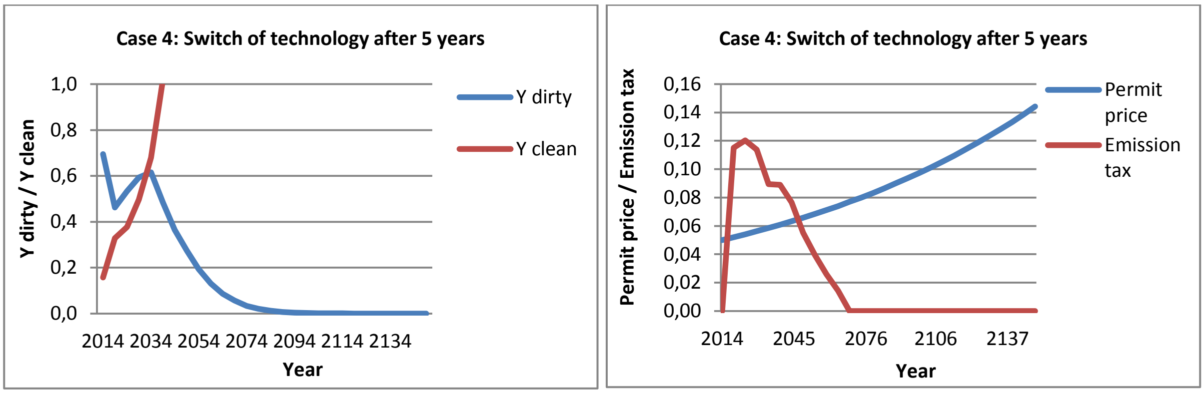


Figure 5: The use of dirty and clean input factors and the emission tax path when the technology switch takes place after 5 years.

Productivity gap between global and local productivity

A further interesting question is whether the developing country is able to catch up with the productivity of the industrialized world. Is learning by doing in the developing country sufficient to reduce the gap in productivity between the two regions over time? The results show that the gap in productivity is only reduced in the cases where global productivity stagnates and remains constant at a certain level. The developing country is only able to catch up with the dirty technology in the case where the global switch to clean technology happens already in period 1. The difference in productivity between the industrialized and the developing country for the dirty technology reaches zero in this case. When the global dirty technology front stagnates, the productivity of dirty technology in the developing country is able to catch up. In all the other scenarios the gap increases. This might indicate that the parameter μ is set too low. In the present simulations the productivity growth in the industrialized countries is higher than the productivity growth in the developed countries, and therefore there the productivity gap is increasing despite the technology diffusion and the learning by doing-effect. These effects are not sufficient to compensate for innovation in the industrialized countries. An interesting extension of the country level model would thus be to let μ approach 0,99 and examine if this has an effect on the productivity gap.

The pattern is repeated for the productivity of clean technology. In this case, the developing country is only able to catch up with the global technology frontier in the case where there is no switch to clean technology. In that scenario, the global productivity of clean technology remains low and constant through the whole time frame of the model. Again the results show that the learning by doing-effect in the developing country is unable to compensate for the difference in productivity unless global productivity stagnates. The same change in μ would be interesting to investigate for these cases.

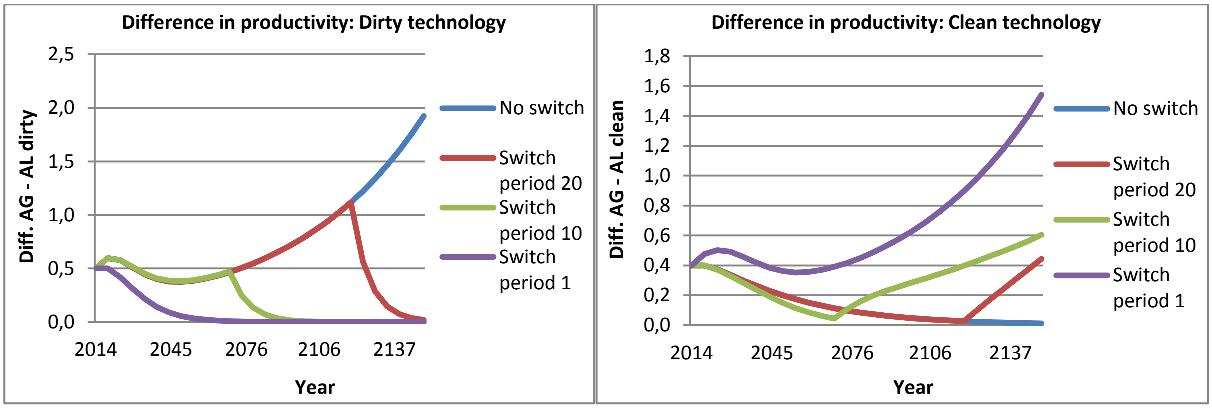


Figure 6: The differences in productivity between the global frontier and the local productivity level for dirty and clean technologies.

Counterfactual scenarios

Based on the results from the technology switch after 50 years and after 5 years, an interesting question arises. What would happen if the emission tax was pegged to the permit price? In the scenarios where there is no shift in technology, or the shift takes place after 100 years, I would not expect any relevant change. In these cases, the emission tax already increases at the rate of the permit price. In the other scenarios where the emission tax follows a very different path, the counterfactual paths could differ.

With this question in mind, I construct counterfactual paths where the emission tax is pegged to the path of the permit price. As expected, in the scenarios with no technology shift, or a shift in the distant future, the counterfactual paths are not significantly different from the original simulations. In the scenario with a technology shift after 50 years, however, there are differences. Firstly the shift to clean technology happens one period later in the counterfactual scenario, and the whole path of clean technology is at a lower level than in the original case. See figure A5 in the appendix. The most prominent change however, is the increase in the price of the clean input factor in the counterfactual outcome. The results show that the emission tax contributes to keeping the price of the clean input low, thus increasing competitiveness. There is no significant difference in summarized, discounted utilities between the counterfactual and the original scenario.

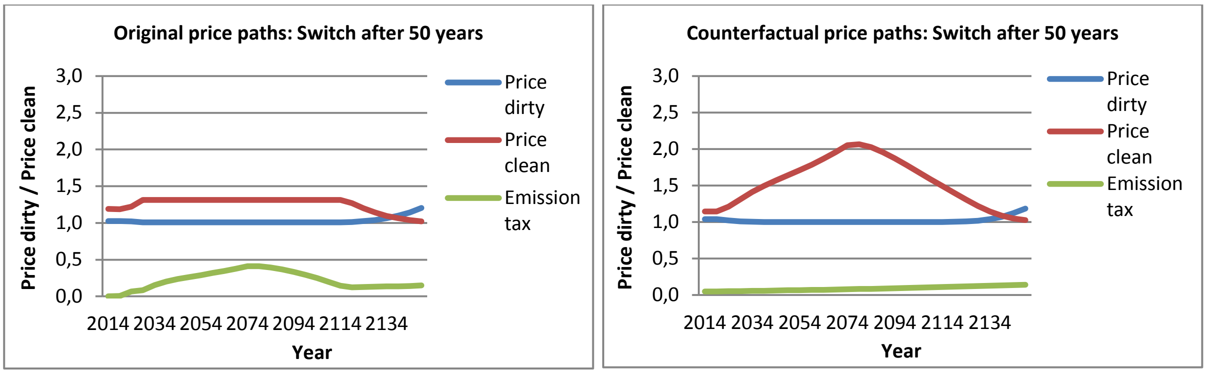


Figure 7: The original and the counterfactual price paths for case 3, where the technology switch takes place after 50 years.

In the case with a technology shift after 5 years, the counterfactual scenario shows the technology shift to clean technology taking place two periods later than in the original scenario. The clean technology path is also here at a lower level for the counterfactual outcome than the original simulations. The counterfactual path shows an increased use of the dirty technology. The counterfactual price paths for the clean input factors do not differ much from the original ones in this case. The counterfactual price starts at a level slightly higher, but they both reach the lowest possible price level by the year 2060. The price relation between dirty and clean input prices, equation (4) is normalized to one, and hence absolute values contain no information. There is no relevant difference in summarized discounted utility in the two cases. These counterfactual results tell us that the high emission tax has influence in the short and medium run, but that in the long run, both the original and the counterfactual scenario converge to the same path.

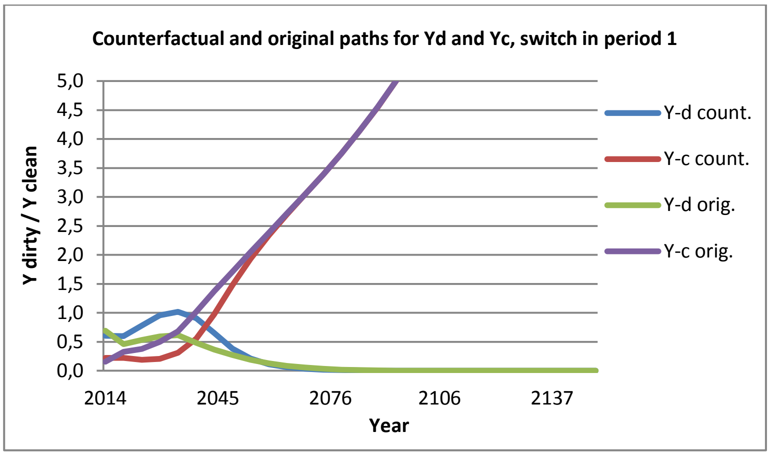


Figure 8: The original and counterfactual path for dirty and clean input factors in case 4 where the shift in technology takes place after 5 years.

5.3 Sensitivity analysis

Before closing the numerical illustration, I include a few sensitivity analyses. It is of interest to determine whether changes in the calibrated parameters affect the outcome significantly, and whether the model results are particularly responsive to changes in some of the parameters. Therefore I will increase the number of model periods, add a scenario with a technology shift after 25 years, investigate changes in the parameter μ and θ due to the limited theoretical foundation and apply different elasticities of substitution and discount rates.

The number of model periods is first increased from 40 to 50. The period extension confirms that some unexpected increases in the emission tax in the last period in cases 1 and 2 are due to end-period-problems. The increase always occurs in the last period regardless of the time frame of the model, and thus this result can be neglected. In case 2, the 10 extra periods further confirm the hypothesis that clean technology will take over when the technology shift takes place after 100 years. It is however necessary with a longer time frame for this feature to be visible. Cases 3 and 4 remain unchanged when the extra periods are added.

To check the robustness of the emission tax pattern, I add a scenario with a shift in technology after 25 years. The results reveal coherence throughout the model. The pattern is similar to the one in case 3 with a technology shift after 50 years. The difference only entails a little less use of dirty technology and a slightly slower tax increase in the extra scenario. The emission tax also approaches zero a little earlier. These results are all consistent with an intermediate scenario between the cases with a switch after 50 years and after 5 years.

Changes in μ and θ

Next, I test different values for the parameter μ, the technology transfer parameter in equation 23, which expresses the rate of learning by doing. If μ is low, the learning by doing-effect is relatively weak. I would thus expect a later switch to clean technology than if μ was high and vice versa. In the original model μ was set to 0,5. In the sensitivity analysis I change it to 0,4 and 0,7, respectively. When $\mu = 0,4$, the baseline case and cases 1 and 2 remain unchanged. In case 3, the use of clean technology passes the use of dirty technology one period later, and the tax reaches zero two periods later than in the original scenario. In case 4, use of clean technology passes use of dirty at exactly the same time, but the tax reaches zero one period later than in the original case. These are changes consistent with theory, but the effects are not very strong.

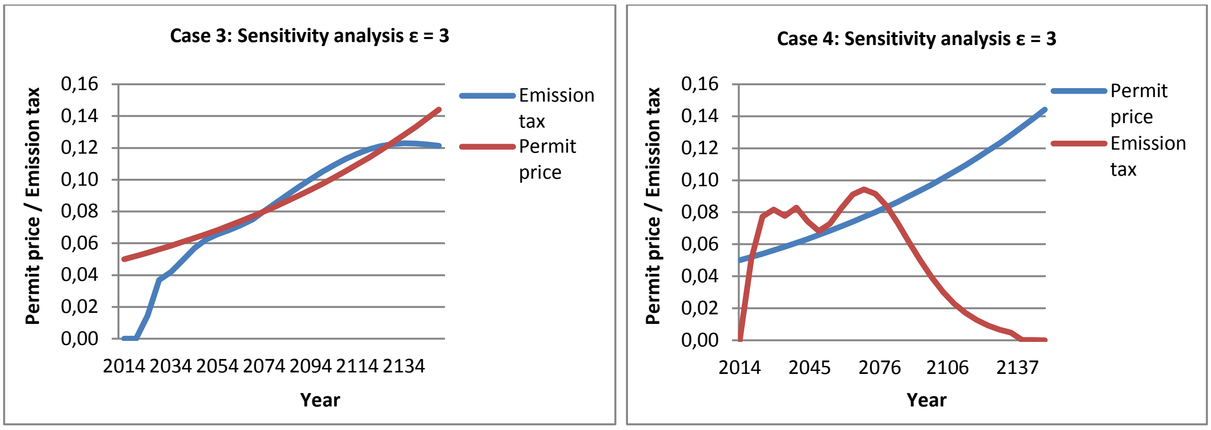
When $\mu = 0,7$, the speed of the learning by doing process is increased, and therefore I expect the shift to clean technology to happen sooner. I further expect the emission tax to reach zero at an earlier point in time. Again there are no significant changes in the baseline or in cases 1 and 2. In case 3, the use of clean technology passes the use of dirty technology one period earlier than in the original model. The tax reaches zero one period earlier as well. These results are consistent with theory. In case 4 there is no significant difference between the scenarios where $\mu = 0,5$ or 0,7, a result which is rather unexpected. When investigating the productivity gap between local productivity and the global frontier for clean technology, the results do however show a difference between the two levels of μ. When μ is high, the productivity in the developing country approaches the global technology front faster than if μ is low. Change in μ, does affect the speed of learning by doing. The results are consistent with the theory, although the effects of the changes are relatively small. This could result both from the lack of precision of the software and the fact that the model does not contain detailed enough information. Due to this the effects of small changes are not easily shown.

The second parameter in the technology transfer relation is θ. In the original simulations $\theta = 1$, and hence has no influence on the results. Theory suggests though that when accumulated use of the input factor in the denominator increases exponentially instead of linearly, the learning by doing-effect increases. When θ is increased to 2 the modified results show the same pattern as in the original scenarios, but with a slightly higher effect. The increase in θ has no significant effect in cases 1 and 2. In case 3 a marginal reduction in the emission tax is visible, and case 4 further shows a little stronger reduction in the emission tax relative to the original model simulations. When θ is increased to 3, the exact same pattern of changes is shown as in the sensitivity analysis when $\theta = 2$, although the size of the tax reduction is a slightly higher. The results show changes in line with theory predictions, although the changes are not strong. The model results are thus not particularly dependent on this parameter.

Changes in ρ and ε

In the last part of the sensitivity analysis, I change the parameters ρ and ε, and apply the other values analyzed by Acemoglu et al. (2012). The original country level model simulations contain the Nordhaus discount factor of $\rho = 0,015$. In the sensitivity analysis I apply the Stern discount factor of $\rho = 0,001$. Cases 1- 3 show no significant changes from this reduced discount rate. Case 4 shows a marginal increase in the emission tax and otherwise the same pattern as in the original model simulations. These results confirm the conclusion of Acemoglu et al. (2012), where they also show that the discount factor is of little importance when the elasticity of substitution is high. In their numerical analysis the configuration $[\varepsilon = 10, \rho = 0,001]$ gave the same results as $[\varepsilon = 10, \rho = 0,015]$ and consequently was left out from their further analysis.

The final test is an application of the low elasticity substitution, $\varepsilon = 3$, for the two input factors. The case witch no switch to clean technology, does not show any changes from the original simulations. In cases 2 - 4 however, there are substantial differences. The low elasticity of substitution leads to changes in the use of the dirty and clean input factors. In case 2 where the technology switch took place after 100 years the original simulations showed stagnation in the use of both the dirty and the clean input factors. When the elasticity of substitution is reduced, there is a steady decline in the use of the dirty input factor matched with a steady increase in the clean input factor from period 25. Case 3 continues to show the declining path of the dirty input factor, but without the drop to zero. A more drastic change in this scenario is that the path of the emission tax changes completely. It becomes similar to the patterns in cases 1 and 2, where the emission tax follows the path of the international permit price. Due to the reduced tax, there is also an increase in the price of the clean input factor.



Figur 8: Emission tax paths for case 3 and case 4 when ε = 3.

The pattern in case 4 is a continuation of the one depicted in case 3. The use of the dirty input factor declines more slowly and approaches zero in the last model period as opposed to the original scenario where it reaches zero in period 15. The emission tax follows the path of the permit price for 12 periods, before it gradually declines to zero in period 26. This is a contrast to the high elasticity of substitution scenario where the emission tax drops to zero in period 12. These results show that the model is highly responsive to changes in the elasticity of substitution, and consequently the assumption about the elasticity of substitution is essential for the bell shaped emission tax pattern to be present. If the substitutability between the dirty and the clean input factors is low, an increased emission tax cannot induce reduction in the use of the dirty input factor. In the local framework it is costly to speed up the learning process. When there is low substitutability between the input factors, learning does to a large degree happen by itself. More of the clean input factor is used at all time because it is not possible to substitute away from it. Consequently it is not optimal to levy an additional cost of increased learning when learning already happens. When substitutability is high, use of the dirty input factor takes over and an emission tax is necessary to compensate for this. This need is no longer present when the substitutability is low.

Model weaknesses

The AABH model was criticized by Hourcade, Pottier and Espagne (2012). Parts of this criticism are relevant to the country level model as well. Therefore I will review the particular points of the criticism which applies to the local model. First, Hourcade et al. question the choices of parameters and point out what they call “structural problems of the AABH model”. They conclude that the theoretical and empirical foundation for the choice of elasticities of substitution is weak, and that the calibrations of $\varepsilon = 3{,}10$ are implausible. In their comment they highlight the fact that all energy sources might be fairly substitutable sometime in the future as innovation widens the range of technological possibility, even when this is not the case today or in the short and medium term. They argue that neither gas nor coal can easily substitute liquid fuels used in internal combustion engines. Further, they claim that the short and medium term elasticity is much lower than the calibrations by Acemoglu et al. This is due to the inertia of existing equipment and to the technical constraints imposed on the system by the energy carriers that transform primary into final energy. In the country level model, this problem seems to be avoided due to the interpretation of measuring consumption in terms of energy, and the fact that clean and dirty energy are highly substitutable. The sensitivity analysis shows that the model results are dependent on the high elasticity of substitution and thus it is relevant to include the critical comment of Hourcade et al.

The second critique of Hourcade et al. concerns the law-of-motion of the CO_2 concentration. They suggest “more scientifically based climate dynamics”, and their analysis consequently shows that carbon taxes are never zero even in the most optimistic cases where the two input factors are strong substitutes. Independently of their choices of parameters, this confirms that the need for regulation is permanent and not transitory as in the results of Acemoglu et al. If the law-of-motion of CO_2 concentration was different, this could indeed affect the results of the country level model. It is not within the scope of the thesis to investigate this further, but it represents a potential model weakness.

In addition to the critique of Hourcade et al. another shortcoming of the country level model is the lack of trade specification in the technology transfer relation. The amount of trade between a developing country and an industrialized country is not specifically included. Coe et al.(1995) showed that a developing country`s total factor productivity depends on three important variables: Factor productivity in the developing country is larger the greater its foreign R&D capital stock, the more open it is to trade with the industrialized countries, and the more educated its labour force is. They conclude that R&D spillovers from industrialized countries to less developed countries are substantial, and that international trade plays an important role in these theoretical arguments. They present empirical evidence that the growth of total factor productivity in developing countries is positively and significantly related to R&D in their industrial country trade partners and to their openness to trade with industrial countries.

Coe et al. highlight the importance of trade for spillovers between industrialized and developing countries. This would also affect learning by doing in the developing country, and therefore could have been more explicitly modelled in the equation of technology adoption, equation (23). In the present technology transfer equation this effect enters through the technology transfer parameter, μ .Including the amount of foreign trade in a developing country specifically would be an interesting extension.

5.4 Discussion

For a small developing country the optimal local policy is highly dependent on the policies of the global community. In the cases where there are no global investments in clean technology, or the shift in technology occurs in the distant future, there is only a marginal amount of learning by doing in the small country. Consequently, national investments in clean technology are too expensive to be welfare enhancing, and therefore the developing country will continue to primarily use dirty input factors in production. The emission tax follows the increase of the permit price. It can be interpreted as a pigouvian tax which corrects for the environmental externality, but it does not contribute to a shift in technology. The lack of learning by doing-effect is dominant.

However, if the global switch occurs after 50 years or after 5 years, a different pattern will emerge. In these cases it is optimal for the developing country to participate in the switch to clean technology. The learning by doing-effect is present, sufficiently close in time, for the technology shift to pay off for the developing country. In these two scenarios the use of dirty input factors goes to zero over time, and the use of clean input factors accelerates and takes over completely.

The emission tax on the dirty input factor behaves quite differently in cases 3 and 4. For a period of time until profitability of the dirty input factor is sufficiently reduced, and the use of the clean input factor becomes profitable, it is optimal to impose a rapidly increasing emission tax. As the use of the clean input factor takes over, the emission tax drops to the level of the permit price, and follows the path of the permit price onwards. This uncommon pattern can be interpreted as a possibility for the developing country to catch up with new technology. When there is a global switch to new technology, the developing country faces the risk of falling behind. Imposing a higher emission tax in the short run strengthens the competitiveness of clean technology. Assuming that the only channel for learning in the developing country is learning by doing, it is essential to increase the utilization of new technology. This can only be done by reducing the use of dirty technology. The numerical simulations of cases 3 and 4 show the optimal emission tax as high and increasing until the use of clean technology is higher than the use of dirty technology.

Examining the consumption patterns in the different scenarios the analysis shows that these are always increasing but due to different reasons. In the baseline and the first scenarios it is optimal to consume everything, despite the reduction in environmental quality. This is because of the lack of influence the developing country has on the environmental quality. Reduced consumption will not result in improved environment, and consequently it is optimal to consume everything. When the technology shift takes place after 100 years, there is a temporary reduction in consumption before the clean technology takes over. In the cases where the global switch occurs after 50 or 5 years respectively, the clean technology becomes sufficiently productive to result in increased production immediately. This leads to increased consumption over time.

In addition the results show great dependence on the elasticity of substitution. It is a crucial assumption that the elasticity of substitution between dirty and clean input factors is high. In the sensitivity analysis where $\varepsilon = 3$, the outcome changes, and the bell-shaped emission tax pattern is absent. As previously mentioned, the comment of Hourcade et al. (2012) criticizes the calibrated elasticities of substitution in the AABH model, and claim that these are implausibly high. The model specification of the country level model interprets production in terms of energy. This makes the assumption about high substitutability more plausible, but the dependency on this particular parameter calibration is important to bear in mind.

6 Conclusion

The Kyoto Protocol establishes the view that the responsibilities for global emission abatements are “common but differentiated” (UNFCCC, 1998). In addition the UNFCCC (1992) state that the developed countries should take the lead in combating climate change and the adverse effects thereof, contributing more to global emission reductions than developing countries. These principles can be transformed to policies in various ways. Kverndokk et al. (2014) and Rosendahl (2004) suggest reduced carbon taxes in developing countries as a method to achieve the goal of differentiated responsibilities between industrialized and developing countries. The results in this thesis suggest, however, that this could in fact be doing the developing country a disservice.

In this thesis I have presented the AABH model of directed technical change, and adapted the global framework to a local framework for a developing country. The adaptation includes the following assumptions: (1) A technology adoption equation where the developing country can accumulate knowledge of new technology through learning by doing. (2) The learning speed increases with the utilization of the particular technology. (3) Finally the developing country enters an international climate agreement with a cap-and trade system for emissions and an international permit price. The optimal emission tax path for the developing country is analyzed in four scenarios, where the time frame for the global investment in clean technology differs.

The results of the numerical analysis show that the timing of the global technology investment is decisive. Given that a global shift towards technology or a sufficient increase in clean R&D takes place within the next 50 years, it would be optimal for a small developing country to deviate from the classic emission tax path. Instead of letting the tax increase at the rate of the permit price, the optimal path for the emission tax should rather be bell-shaped and excessively higher than the permit price until the use of clean technology starts to accelerate. The emission tax path should then correspond to the permit price until the use of dirty technology reaches zero. The condition for these results to hold is that the global shift in technology investments takes place at an early point in time and that the substitutability between the clean and dirty input factors is sufficiently high. In the scenarios where there is no technology shift or a shift in the distant future, the numerical analysis shows a complete absence of the bell-shaped emission tax pattern. The same applies when the elasticity of substitution is low. In these cases there is the traditional emission tax pattern instead, which increases with the rate of the permit price.

The mechanism which drives these results is the learning by doing effect. The more clean technology is utilized, the faster clean technology becomes productive and is able to compete with dirty technology. The results suggest that if learning by doing-effects are present in the developing country, and a global switch to clean technology will take place within the next 50 years, excluding the developing country from participation in the transfer to clean technology can be costly. It restrains the developing country`s possibilities of acquiring knowhow of new technology and thus reduces chances of development in the future.

In the context of the UNFCCC principles these results suggest that the content of the common but differentiated responsibilities should not include reduced carbon taxation in developing countries if a global switch to clean technology is approaching and substitutability between clean and dirty sectors is high. A temporarily increased emission tax will instead contribute to making the clean technology competitive, and opening possibilities for increased growth and consumption in the long run. The latest IPCC report (2014) is clear regarding its recommendations of investment in clean technology. If the 2 °C target is to be met, excessive investments in clean technology must be realized sooner rather than later. If the global community takes these concerns seriously and is able to unite on a global path of emission reductions, the role of the developing countries will become important. Good environmental policies could become a distinction between the developing countries which are able to take the leap to clean technology and increased growth, and those which will continue to fall behind.

The results in this thesis are based on a limited analysis impairing their generalization value. Further studies, including additional sensitivity analyses, thorough analyses of actual costs in addition to discounted utility and empirical data are necessary to conclude about optimal environmental policies in developing countries. Despite the problem of generalizability of the results, they convey sufficient insight into the role of carbon taxation in a developing country to motivate further research in this field.

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Appendix

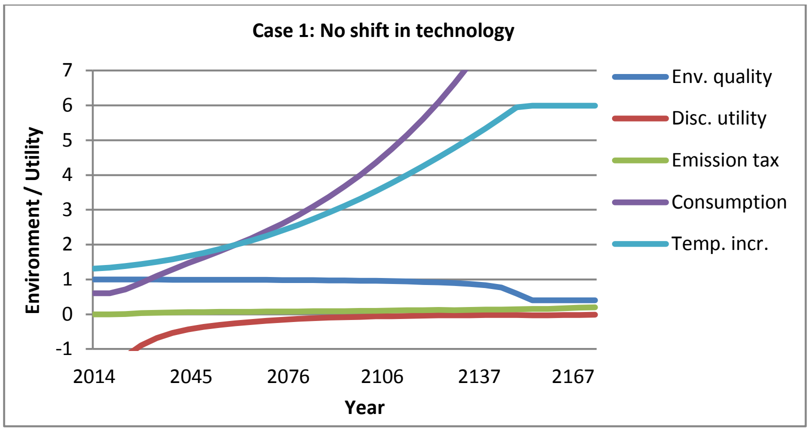

Figure A1: Environmental quality and utility in case 1 where there is no switch to clean technology.

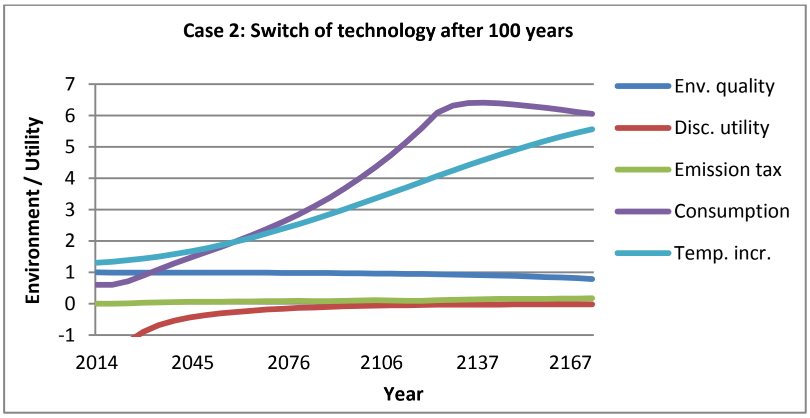

Figure A2: Environmental quality and utility in case 2 where the switch to clean technology takes place after 100 years.

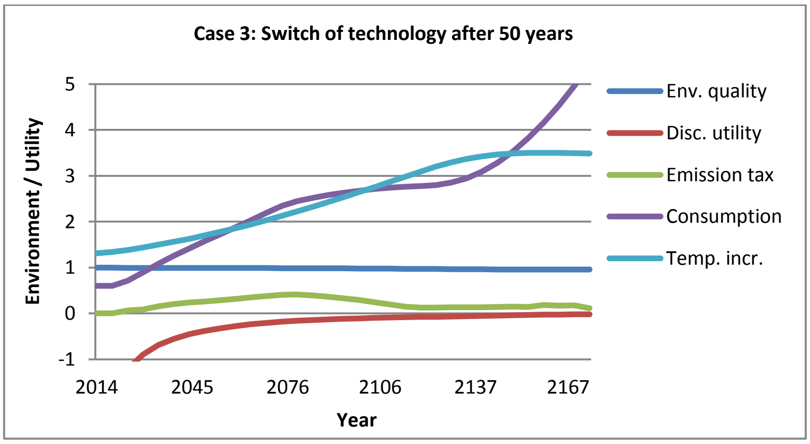

Figure A3: Environmental quality and utility in case 3 where the switch to clean technology takes place after 50 years.

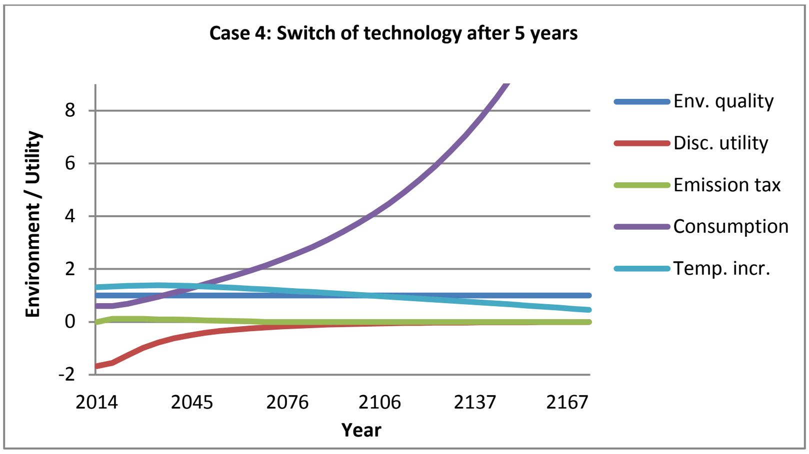

Figure A4: Environmental quality and utility in case 4 where the switch to clean technology takes place after 5 years

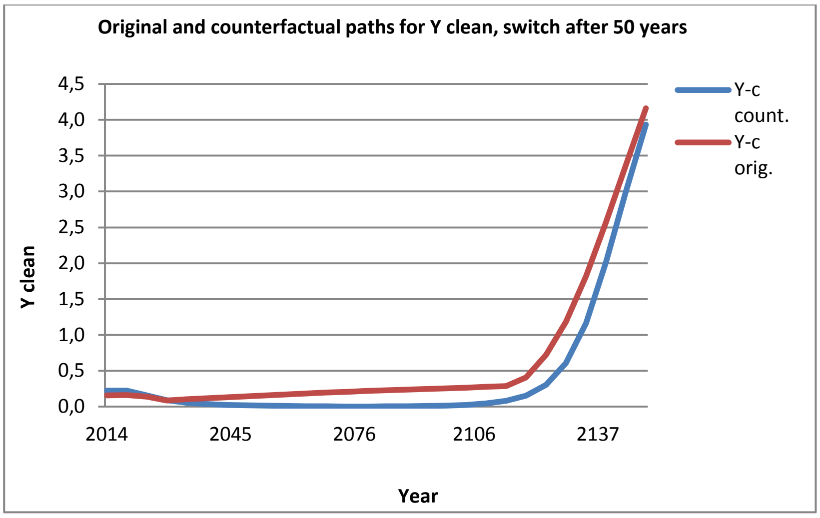

Figure A5: Original and counterfactual paths for Y clean in case 3 where the switch to clean technology takes place after 50 years.

The numerical simulations for the sensitivity analysis can be obtained by contacting the author.