The Economics of Environmental Innovation, Regulation and Commitment

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Grischa Sebastian Perino

geboren in Oberkirch.

To Vanessa

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Chapter 1

Introduction

The production of economic goods is fundamentally linked to environmental degradation by means of pollution, waste and land conversion. This link gives rise to a management problem that lies at the heart of environmental and resource economics.[1] Research addressing this problem has two main objectives: (a) to find the optimal balance between gains from economic production and costs of the associated environmental degradation given a set of technologies; (b) to optimally invest into research fostering technological progress that relaxes the trade-off between productive activities and the natural environment and human health. Meeting those objectives at the same time constitutes the optimal pollution and research policies. The optimal pollution policy tackles the optimal scale of production and the optimal mix of technologies at any point in time. The optimal research policy determines the optimal timing, size (quantity) and type (quality) of innovations. In principle, all of these factors are to some degree endogenous. Starting with the scale of production (Pigou 1920), this endogeneity has been incorporated into the economic literature.

The impact of new technologies on the optimal extraction path and the optimal mix of technologies has first been studied in resource economics. Dasgupta and Heal (1974) analyze the optimal extraction of an essential but exhaustible natural resource assuming an exogenous and uncertain arrival of a backstop technology. A backstop technology in the resource extraction problem is a technology giving access to a resource with an infinite stock. More recently, in the literature on stock pollutants, "*the backstop*" has become a shorthand for perfectly clean technologies that solve the pollution problem once and for all. Hence, in both cases innovation is able to provide a terminal solution to the extraction or pollution problem. Hung and Quyen (1993) introduce the issue of optimal timing of research investments in a resource

[1] For a review of research questions in environmental economics see Cropper and Oates (1992).

exploitation model, while Baudry (2000) does so in the context of stock pollution. Both endogenize the decision when to invest in the development of a backstop.

The above literature is concerned with the optimal timing of innovations, but keeps the type of technology, i.e. the backstop, fixed. Moreover, it assumes that the new technology is a backstop implying that research always solves the pollution problem once and for all. Therefore the question how often R&D is best carried out is trivial. A major contribution of this thesis is to consider a new type of innovation that makes the timing and frequency decisions in R&D more realistic.

1.1 Green Horizontal Innovation

Parts I to III broaden the concept environmental innovation by introducing the idea of 'green' horizontal innovation. It incorporates the important empirical observation that new technologies designed to solve a particular pollution problem often come with strings attached. They are generally not strictly superior to the old technology. This non-superiority is characteristic for horizontal innovation. In order to qualify for the 'green' innovation category, the technology has to differ from the others in the type of pollution emitted. Given pollutants contribute to different environmental problems that do not interact differentiation of the pollution, and hence technology portfolio, is socially desirable if marginal damages are increasing within each pollution type. In contrast to the well established product differentiation argument (Dixit and Stiglitz 1977) the social gain of a new technology does not rest on the creation of additional demand. All technologies produce perfect substitutes. The social gain of a new technology builds on the opportunity to spread output between more technologies with specific pollutants and thereby reduce the marginal damage of emissions per unit of output.

A prominent example for green horizontal innovation is the history of refrigeration. In the 30's poisonous cooling agents have been substituted by chlorofluorocarbons (CFCs), which later turned out to deplete the ozone layer. After the ban of CFCs by the Montreal Protocol, newly developed substitutes became available. However, they are associated with stock pollution and health risks of their own. Energy production faces similar trade-offs between the lesser of two evils. While fossil fuels such as oil, gas and coal contribute to global warming, the main alternative for electricity production, nuclear power, results in the build up of radioactive waste and has the 'residual' risk of a catastrophic accident. Moreover, most end-of-pipe technologies convert one type of pollution into another one. For example, scrubbers and electrostatic precipitators remove lead and particulate matter (PM) from exhaust air by converting them into other forms of waste.

Green horizontal innovation occurs at all relevant scales. It reaches from entirely different production processes (as in the case of energy production) to small scale end-of-pipe solutions, like catalytic converters in cars. The latter reduce emissions of hydrocarbons and carbon monoxide at the cost of higher sulphur oxide emissions.

All these examples have in common that, by reducing one type of damage, the new technology gives rise to another. Research might therefore not solve the pollution problem but dilute it. Sequences of innovations as in the case of refrigeration are a naturally arising pattern under green horizontal innovation. This very nature of green horizontal innovation poses new challenges to the management problem. Both, the optimal timing of R&D and the management of the available technology portfolio, become more sophisticated. Instead of only one, an endogenous number of innovations is considered that are undertaken at endogenously determined points in time. Therefore, a more demanding methodical approach has to be employed.

However, the case where all new technologies are horizontal innovations is only a special case of the more general model analyzed in part I. The second contribution is to allow for technological uncertainty associated with the R&D process. Ex-ante the planner attaches beliefs about the type of technology to be developed by the next innovative step. Technologies come in two varieties: as green horizontal innovations, labeled 'boomerangs', and as backstops that solve the pollution problem once and for all. In the baseline model the planner's beliefs are fixed. However, chapter 6 allows for rational learning based on the outcome of previous R&D projects.

1.2 Implementation and the Choice of Instruments

Deriving socially optimal plans for production and research is only the first step toward an actual policy. The literature on the implementation of environmental policies was started by the seminal contribution of Pigou (1920). Over time, the set of employed policy instruments has grown and now includes command and control, tradeable permits, several forms of liabilities, auctions and combinations thereof. Moreover, it is necessary to consider instruments such as patents and R&D prizes, in order to discuss the optimal timing of research.

The joint implementation of optimal pollution and research policies gives rise to another set of issues, namely the interaction between the two types of instruments and the resulting trade-offs between static and dynamic efficiency.[2] This strand of the literature focuses on the impact of environmental policies on research incentives. Initiated by Magat (1978), who compares emission taxes with a command and control scheme, the set of instruments and cases covered has been extended, e.g. by Milliman and Prince (1989) and Jung et al. (1996). These studies focus on industry wide adoption. This approach has been criticized by Requate and Unold (2003), who consider the equilibrium incentives of individual firms to adopt.

A more explicit analysis of the effect of environmental policies on the incentives created by patents is conducted by Laffont and Tirole (1996b) and Denicolò (1999). Under certain conditions, they establish equivalence of taxes and permits both with respect to static efficiency as well as in terms of dynamic incentives for R&D. However, dynamic efficiency can be seriously limited if the government is unable to commit on future environmental policy ex-ante.

The reverse interaction, namely whether patents affect the performance of environmental instruments, has largely been ignored so far. A notable exception is Requate (2005a). He finds that the market power created by patents distorts adoption decisions both under emission taxes and permits. Part II extends this approach to various settings and qualifies previous findings by Denicolò (1999).

Moreover, green horizontal innovation calls for new implementation strategies. Part II shows why conventional instruments such as a combination of patents with taxes or permits might fail to implement the desired plans and develops strategies that - at least in principle - are able to overcome these obstacles. If research incentives are provided by patents, only hybrid tax-permit schemes are able to achieve both static efficiency and positive research incentives. That is, because by definition patents create monopoly power.

Allowing for more flexibility with respect to the design of environmental instruments, however, poses challenges in situations with only one pollutant and a government which is unable to commit to details of future policies. Hybrid schemes give the government more controll over equilibrium quantities. Although increased control generally improves static efficiency, it can be detrimental to research incentives in situations where there is a trade-off between the two objectives. Part III shows for a number of exemplary cases that an endogenous design of environmental instruments often reduces and sometimes destroys incentives to invest in R&D. In

[2] For reviews see Jaffe et al. (2002) and Requate (2005b).

addition to the endogenous design of instruments, the impact of a revenue objective by the government is analyzed. Somewhat surprisingly its effect on research incentives is ambiguous. Although one might expect this objective to increase the incentives to effectively expropriate the patent holding firm (or not to grant a patent in the first place), this consequence only holds in some situations.

The results of part III highlight the well known conflict between static and dynamic efficiency with patent based research incentives and show that it is relevant in the context of environmental innovation. Previous studies have tended to ignore this issue.

The insights of parts II and III are used to derive implementation strategies for the optimal policies under multiple green horizontal innovation presented in part I.

1.3 Implementation and the Ability of a Government to Commit

Endogenous design of environmental instruments reflect an increase in the government's set of choice variables. Moreover, in some cases revenue objectives intensify the time-inconsistency problem in policy making. Credible commitments to future instrument choice and design bear a large potential to increase the long-run efficiency of the economy. Part IV investigates how the internal organization of government can increase its ability to commit.

Rogoff (1985) proposed delegation of specific tasks to an independent agency as an effective mean for a government to credibly bind its hands . However, this view has been criticized for taking commitment on the institutional structure, i.e. delegation, for granted (McCallum 1995). Part IV takes up this critique and uses the same commitment technologies to induce credibility in policies as well as in institutional choices. It presents a model where both delegation and the level of commitment are endogenous. While in a deterministic setting delegation has no effect on commitment, as predicted by McCallum (1995), this relation no longer holds if exogenous shocks to the economy become relevant. Delegation then allows to reduce the trade-off between flexibility and credibility. Without delegation the commitment not to change a specific policy reduces the government's ability to adjust to shocks. If, however, the policy choice is transfered to an independent party, the level of commitment and the ability to adjust to unforeseen changes are no longer equivalent. As a result, a government has more incentives to invest in commitment if it delegates. Hence, although both, the actual policy choice and the institutional structure, are subject to the same commitment technology, policies are more credible under delegation. This finding is in line with empirical evidence on central bank independence. The results derived in part IV are of relevance beyond the area of optimal environmental regulation.

1.4 Methodology

The starting point of this thesis is to incorporate an empirical observation, green horizontal innovation, into the economic literature. The analysis, however, is theoretical in nature. The employed models are tailored to capture the essence of the problems and results are stylized. Nevertheless, the policies derived are in line with real world phenomena. An econometric analysis testing and calibrating the results lies beyond the scope of this thesis, but provides fruitful research for the future.

Part I takes a social planner's perspective and studies first best pollution and R&D policies in an infinite horizon, continuous time, multi-stage optimal control problem. In this setting the number of state and control variables is endogenous. New technologies introduce a new stock pollutant and a new output to be controlled by the planner. Moreover, the timing and number of innovations are subject to the planner's discretion. The tools to study multi-stage dynamic optimal controll problems have recently been developed by Tomiyama (1985) and Makris (2001). However, in order to allow for technological uncertainty, i.e. that R&D efforts either produce a green horizontal innovation or a backstop, the established necessary conditions have to be adjusted. The incorporation of a simple form of uncertainty at the switching instances constitutes the methodical contribution of this thesis.

The models in parts II to IV are formulated in a game theoretic setting and the social planner is, generally, replaced by a benevolent government and a private sector. The resulting strategic interaction between players, such as monopoly pricing and time-inconsistency, allows to model relevant issues of implementation and to derive detailed policy recommendations. The setting in parts II and III, with the exception of chapters 14 and 21, spans only two discrete periods in time. Chapters 14 and 21 join the continuous, multi-stage optimal controll problem of part I with the decentralized framework of parts II and III. They show that there is a first best closed loop equilibrium and present the corresponding implementation strategies.

Part I

Green Horizontal Innovation: The Social Optimum[3]

[3]This part is based on three papers jointly written with Timo Goeschl (Goeschl and Perino 2007a,b,c)

Chapter 2

Introduction to Part I

2.1 Backstop Technologies and the Environment

Backstop technologies are a common point of reference in dynamic models of the environment and natural resources, beginning with the influential study by Nordhaus (1973) on exhaustible sources of energy. He defines a backstop as

> *"... a set of processes that is capable of meeting demand requirements and has a virtually infinite resource base."* (Nordhaus 1973, pp. 547-548)

More recently, in the context of the expanding literature on the economics of stock pollutants, "*the backstop*" has become a shorthand for perfectly clean technologies that do not suffer from a stock pollution problem. In both cases, the backstop allows the decision maker to escape a binding constraint forever.

The existing literature on backstops offers optimal timing rules regarding the phasing in of a backstop in a variety of different settings and under varying degrees of uncertainty. In the area of non-renewable resources, Dasgupta and Heal (1974) study optimal exhaustion when the arrival time of the exogenously provided backstop technology is stochastic. Hung and Quyen (1993) endogenize the decision when to invest in R&D in a setting where the length of time required to develop the backstop is uncertain. Tsur and Zemel (2003) develop a deterministic model with the difference that the backstop can be continuously improved through additional R&D. Just et al. (2005) provide a stochastic, but discrete analysis of a similar problem. In the context of stock pollution Baudry (2000) applies real options theory in a setting where the backstop arrives stochastically after R&D is commenced; and Fischer et al. (2004) consider the optimal investment path for an existing clean backstop technology.

2.2 Green Horizontal Innovation

One type of uncertainty that has not been considered so far in the literature is uncertainty about the characteristics of new technologies. Commonly, models rely on an assumption of technological certainty in R&D: If the backstop is not already available, the next technology to be invented will constitute a backstop. A well defined R&D investment will therefore generate a final resolution of the intertemporal constraint. Although there are a few exceptions (e.g. Baudry (2000)) that allow for the new technology to be cleaner but still polluting, they keep the assumption that the new technology is strictly superior.

Looking at the empirical record, this idea is at least arguable. Some prominent examples like the history of refrigeration illustrate this point. The most important cooling agents, chlorofluorocarbons (CFCs), are a pollutant blamed for the depletion of the ozone layer. Their introduction resulted from the search for a substitute for poisonous refrigerants such as ammonia and sulphur dioxide that due to leakages caused a significant number of casualties. Even such well known figures as Albert Einstein and Leo Szilard, who jointly invented and patented three different refrigeration technologies, each with its own specific drawbacks, were involved in the search for less dangerous technological solutions (Dannen 1997). When CFCs were discovered, they seemed to constitute a backstop since no adverse environmental or health effects were apparent at the time and production sufficiently cheap to allow for widespread diffusion during the mid-20^{th} century. However, after humanity became aware of their ozone-depleting effect and the associated damages, they were banned by the Montreal Protocol. However, although newly developed substitutes such as HCFC-123 were demonstrated to feature a more benign stratospheric chemistry, they also imply a different stock pollution problem on account of decaying into toxic pollutants such as trifluoroacetic acid (Likens et al. 1997).

Primary substitutes for fossil fuels, nuclear energy and ethanol, may provide advantageous properties with respect to exhaustibility and climate impact, but while the former involves the production of long-lived stocks of radioactive waste the latter is suspected to induce increases in ozone-related mortality in major cities (Jacobson 2007). Other examples of green horizontal innovation are petrol and diesel engines used in cars and chlorine[1] production.

Moreover, most end-of-pipe technologies fit into the green horizontal innovation

[1] See Snyder et al. (2003)

category. In automobiles catalytic converters reduce emissions of hydrocarbons and carbon monoxide but at the cost of higher sulphur oxide concentrations (Tietenberg 1992). Hydrocarbons are precursors of low level ozone, carbon monoxide is poisonous and sulphur oxides cause acid rain. Scrubbers and electrostatic precipitators remove lead and particulate matter (PM) from exhaust air by converting them into waste water or solids.[2] Harrison and Antweiler (2003) find that the Canadian industry has made extensive use of end-of-pipe solutions and that significant shifts in the composition of pollution has occurred during the nineties.

These are only some illustrations of a more general observation, namely that technologies developed in response to binding intertemporal constraints may relax those constraints, but will not always allow decision-makers to escape them indefinitely. In such a situation, investments in R&D have to be considered under the premise that the arrival of a backstop is only one of two possible outcomes of the innovation process. Instead, R&D may generate a technology that is novel, but has strings attached in the form of an intertemporal pollution dynamic of its own. The possibility of the intertemporal constraint recurring even after R&D resources have been expended is the possibility of technological '*boomerangs*'.

Despite its practical importance, green horizontal innovation has received little attention in the economics literature so far. Moslener and Lange (2004) compare the prospects of a new technology with initially uncertain environmental effects to an established one that causes well known damages. Necessary and sufficient conditions for a new polluting technology to be desirable have recently been derived by Winkler (2005). There is also a related growth literature where technologies using different environmental resources compete (Chakravorty et al. 1997) or innovation creates a new damage (Smulders et al. 2005). However, the optimal mix of different damages, the potential for multiple innovations and technological uncertainty are not considered.

2.3 Research Questions

In this part, the implications of allowing for technological uncertainty over innovation outcomes on optimal R&D timing is studied, choosing the context of stock pollutants as a setting. To model technological uncertainty, consider a decision-maker who attaches a probability to the possibility that new technologies may not turn out

[2] See Greenstone (2003)

to be the clean backstop that will solve the pollution problem once and for all, and allow these beliefs about the probabilities to become decision-relevant. This small change in the assumptions about the decision-maker's view about the likely environmental characteristics of new technologies has important repercussions for his thinking about pollution policies and R&D timing. The change extends the set of possible future states of the world to situations where new technologies turn out to have undesirable properties. This means that R&D may have to be undertaken more than once in order to solve the pollution problem. In fact, the possibility of lengthy sequences of failures to find a backstop despite R&D investment can no longer be excluded by the planner. This has repercussions for the optimal pollution policy since future costs of current emissions depend on the degree of uncertainty over the discovery of a backstop.

While it seems clear that the possibility of receiving (possibly multiple) technologies of the '*boomerang*' type in the quest for a backstop should change the optimal prescriptions both for environmental and for technology policy, the precise nature of these changes is less obvious. Should the policymaker respond to the presence of technological uncertainty with higher or lower R&D efforts? Should R&D be carried out on a large scale right at the start (front loaded) or spread out over time? How should the policymaker respond to the invention of a 'boomerang' technology - with more R&D right away or with waiting? Should R&D ever stop even though a backstop has not been found yet? In what follows, a specific setting is developed in which these questions can be answered on the basis of analytical solutions. This is in order to develop a first intuition on the impact of technological uncertainty on optimal R&D and in order to provide a building block for considering more general cases in the future.

Nevertheless, some extensions are discussed in chapter 6. Among these are exogenous and endogenous changes in the costs of R&D, evolving beliefs of the social planner about the probability to develop a backstop by conducting an additional R&D project, asymmetric boomerang technologies and more general social welfare functions. However, in some cases the results remain sketchy, since no analytical solutions exist, e.g. due to the lack of necessary conditions for infinite horizon, multi-stage optimal control problems with an infinite number of switches.

2.4 Outline of the Model and the Methodology Used

The simple and tractable model consists of a production sector producing a single product up to a fixed output constraint, with one technology of the boomerang type available *ab initio*. Production generates a profile of technology-specific pollutants. Once a backstop is available, that part of production carried out using the backstop will produce no pollution at all. Damages are convex in the stock of each pollutant and additive across pollutants, giving rise to gains from diversification in pollutants and hence incentives for conducting R&D even when a backstop is not feasible. To retain a clear focus on the role of uncertainty, other important R&D drivers, such as reductions in unit costs, whose impacts have been established in the literature are excluded from the analysis. R&D has a deterministic component in that at any given time, a new technology with zero stock of initial pollution can be provided at a fixed cost. What is uncertain, however, are the environmental characteristics of the new technology. Under the decision-maker's beliefs, R&D carried out at a given point in time will fail to generate a backstop with a certain probability and will generate a technology involving a new stock pollutant instead. Given this setting, the optimal timing of R&D and the optimal pollution policy are studied. This part focuses on the social planner's perspective. Issues of implementation are treated in subsequent parts.

In order to derive the optimal R&D trajectory recent results on multi-stage optimal control with infinite horizons are utilized. This technique allows to capture a process of technological evolution in which new technologies are added in a discrete fashion. In addition to applying this technique to the question of optimal R&D trajectories, the first application of this technique to a situation characterized by uncertainty over the properties of the next stage of the optimal control problem is presented. This involves a suitable modification of the necessary conditions derived by Makris (2001) and Tomiyama (1985).[3]

2.5 Key Results

Key findings are that in this setting the optimal R&D program (i) is strictly sequential, (ii) has an endogenous stopping point and (iii) there is a constant pollution stock threshold level that triggers research and is above the long run steady state of

[3]For a more formal treatment of deterministic infinite horizon multi-stage optimal control problems see Babad (1995).

pollution stocks (overshooting). Technological uncertainty affects both the optimal timing and the maximum size of the technology portfolio. The optimal pollution policy becomes more sophisticated if research fails to deliver a backstop technology.

Relaxing some of the assumptions of the model yields the following qualifications. If the costs of R&D are decreasing either in the number of already developed technologies (learning by doing) or in time (exogenous technological change) more technologies are developed. The maximum size of the technology portfolio can even approach infinity. In the opposite case, where the costs of R&D increase, innovations become less frequent. Endogenizing the probability to develop a backstop comes in two varieties. If, on the one hand, the social planner believes that sequences of R&D 'failures' (i.e. boomerang technologies) make the arrival of a backstop more likely, then more innovation occurs than under the baseline. However, the sequence of innovations is always finite which contrasts the case of decreasing costs of research. If, on the other hand, the social planner becomes disaffected by a series of boomerangs, the number of attempts (and hence the change to end up with a backstop) decrease compared to the baseline. Relaxing the symmetry assumptions regarding the characteristics of boomerang technologies does not change the qualitative pattern of the pollution and research policies. One exception, however, are different costs of production. If they vary sufficiently across technologies the more expensive types might be abandoned forever at some stage even if no backstop is developed. A feature not present in the baseline model.

The structure of this part is as follows: In the next chapter, the model set-up is described. Chapter 4 develops the optimal pollution policy for a given number of technologies. In chapter 5 the optimal timing of R&D under technological uncertainty is studied. Extensions to the baseline are presented in chapter 6 and chapter 7 concludes this part.

Chapter 3

The Model

The model presented in this chapter is intended to capture the discrete nature of technological change arising from the development of distinct technologies and the uncertainties inherent in developing technologies with previously unknown environmental properties. Key features of the model are a potentially very large number of technologies, an infinite planning horizon, and endogenous timing of R&D. At the same time the model retains the ability to generate analytical results.

3.1 The Environment-Economy Link

First, the environmental side of the model is described, which together with the innovation side describes a setting in which pollution and R&D policies are jointly determined. Environmental outcomes are modeled in the form of the standard stock pollution model common in the literature (Fischer et al. 2004, Baudry 2000). With $n(t)$ potential pollutants $i \in \{1, ...n(t)\}$ present at time t, the stock of each individual pollutant $S_i(t)$ evolves according to

$$\dot{S}_i(t) = \alpha_i q_i(t) - \delta_i S_i(t), \tag{3.1}$$

with α_i denoting the accumulation coefficient per unit of emissions q_i of pollutant i and δ_i denoting the natural rate of decay of its stock.

Technologies and pollutants in this model have a one-to-one relationship such that i denotes both the pollutant and its generating technology. Pollution damage at time t $D\left(S_1(t), ..., S_{n(t)}(t)\right)$ is determined by pollution stocks only and is given by

$$D(S_1(t), ..., S_{n(t)}(t)) = \sum_{i=1}^{n(t)} \frac{d_i}{2} S_i(t)^2, \tag{3.2}$$

with d_i denoting the marginal damage coefficient of pollutant i. Note that pollution damage is additively separable in the square of stocks of individual pollutants and that pollutants therefore do not interact with each other.

The general form of the instantaneous welfare from production at time t is assumed to be additively separable

$$W(t) = \sum_{i=1}^{n(t)} \left[q_i\left(t\right)^{\beta} - c_i\left(q_i, t\right) - \frac{d_i}{2} S_i(t)^2 \right] \tag{3.3}$$

with $c_i\left(q_i, t\right)$ denoting the production cost at time t given output q_i and $0 < \beta \leq 1$. Given the general form of (3.3), there are at least five reasons for conducting R&D in such a setting: (1) Cost reduction (Tirole 1988), thus targeting $c_i\left(q_i, t\right)$); (2) improvements in the output-emission ratio (e.g. Denicolò 1999, Fischer et al. 2003) through searching for products with lower α_i, a backstop being a special case with $\alpha_i = 0$; (3) amelioration of environmental damages through finding less harmful or less persistent pollutants, implying a lower d_i (where $d_i = 0$ again represents a backstop) or a higher δ_i; (4) technological diversification that increases the variety of consumer goods on account of new technologies (Dixit and Stiglitz 1977) if $\beta < 1$ and marginal welfare is hence decreasing in the output of each individual product; and finally (5) technological diversification that increases the variety of existing pollutants because damage is convex in each individual pollution stock but additive across stocks.

All of the reasons mentioned above individually provide positive incentives for resources to be devoted to R&D. Most relevant for a policy problem involving uncertainty about whether the R&D process delivers perfectly clean backstops or imperfect boomerang technologies are the extreme versions of the second and the third case and the last setting where diversification in pollutants is the primary reason for devoting resources to R&D. Therefore, we design a model that strips out all these other well established drivers before exploring the implications of additional factors in chapter 6.

One mechanism underpinning R&D investments then is similar in spirit to the well-known product differentiation models of the "horizontal innovation" type (Gancia and Zilibotti 2005), with one important difference: Instead of increases in the variety of products, it is increases in the variety of pollutants that generates welfare gains by decreasing marginal damages associated with production. In this sense, a process of "green" horizontal innovation of pollution differentiation is modeled. A second mechanism is the quest for a final solution to the pollution problem. The chance to develop a backstop (see next section), adds to the attractiveness of R&D.

As a consequence, the model that follows contains some important simplifications regarding the heterogeneity of pollutants and the shape of the social welfare function: With the exception of the backstop, technologies (and therefore pollutants) are assumed to be symmetric in terms of their coefficient of accumulation $\alpha_i = \alpha$, rate of decay $\delta_i = \delta$, and the marginal damage coefficient $d_i = d$. The backstop on the other hand, representing a 'perfectly clean' technology, is characterized by zero damages and no accumulation such that $d_B = 0$ and $\alpha_B = 0$. For all technologies, costs are assumed symmetric and zero such that $c_i\,(q_i, t) = 0$. Technologies are perfect substitutes ($\beta = 1$) and symmetric in terms of net marginal benefits which are normalized to 1 per unit of output. Aggregate output is exogenously bounded from above as in Baudry (2000). This is an indirect way of taking a downward-sloping demand function and capital stock constraints into account

$$\sum_{i=1}^{n(t)} q_i(t) \leq 1, \tag{3.4}$$

$$0 \leq q_i(t), \leq 1 \quad \forall i \in \{1, ..., n\,(t)\}. \tag{3.5}$$

The symmetry of the technologies in terms of the production-pollution side of the model then simplifies the instantaneous welfare function (3.3) to

$$W(t) = \sum_{i=1}^{n(t)} \left[q_i(t) - \frac{d_i}{2} S_i(t)^2 \right] \tag{3.6}$$

in which boomerang technologies now differ in terms of vintage only and the backstop technology differs in terms of damage intensity. Both the symmetry assumption with respect to boomerang technologies and the shape of the welfare function will be somewhat relaxed in chapter 6.

3.2 The R&D Process

Innovation is modeled as follows: At any time t, society can choose to spend resources $R\,(t)$ which will make available instantaneously and with certainty the $n + 1^{st}$ technology. The point in time when the $n + 1^{st}$ technology is developed is denoted by t_{n+1}. The number of technologies $n(t)$ available for production at t therefore depends on the sequence of past investments $\{t_1, ..., t_n\}$. The environmental characteristics of the new technology are not known prior to its arrival. With probability p, the $n + 1^{st}$ technology turns out to constitute a technology of the backstop type. In the event, the number of technologies remains fixed from then on as there is no further rationale for resources to be spent on R&D in a setting where technologies are otherwise perfect substitutes. With probability $(1-p)$, the $n+1^{st}$ technology is of the boomerang type. Use of the new technology therefore involves the generation of a novel, technology-specific pollutant (see Figure 3.1).

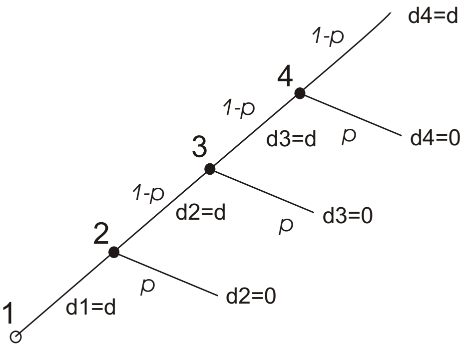

Figure 3.1: Potential Sequence of Innovations

While it is possible in principle that the decision-maker would choose to develop more than one technology at a single point in time, the presentation in the main part abstracts from this possibility. Allowing for multiple innovations at a single point in time significantly adds to the notational burden. It is shown in appendix A.4 that innovation is indeed sequential. Hence, in what follows attention is restricted to a situation in which at any given point in time t, at most one technology is developed.

All new technologies start with an initial stock of pollution $S_n(t_n)=0$ and can at once be used at any level of intensity.[1] For convenience, it is assumed that the current cost of R&D is independent of time such that $R(t)=R$ and that initially, one technology is available such that $n(0)=1$. Furthermore, it is assumed that there is an arbitrarily large but finite number of potential technological solutions M that can possibly be developed. Each of these solutions is a simple lottery. At the instant they are converted into technologies by R&D they materialize either as a backstop (with probability p) or as a *'boomerang'* (with probability $1-p$). Hence, p is independent of both the maximum number of technologies feasible, M, and of the number of technologies already developed, n. This independence is relaxed in section 6.2 when the social planner's belief about the arrival probability p is evolving depending on observation of previous R&D outcomes.

[1] Questions about the optimal accumulation of technology specific capital (as e.g. Fischer et al. (2004)) are not studied.

In this stylized model there are two motives for carrying out R&D. The first is the chance to acquire a backstop and thereby solve the pollution problem once and for all; the second is pollution differentiation: Due to increasing marginal damages in pollution stocks and additive damages across pollutants, a new technology with a new pollutant and a zero stock creates social gains. Individually, these motives generate distinct R&D trajectories. In the absence of gains from pollution differentiation, it is readily apparent that the backstop motive will imply that it is either never optimal to undertake research or, once a certain pollution threshold is reached, investment continues until a backstop is developed. Which state prevails depends on the cost of R&D and the probability to develop a backstop. In the absence of a backstop motive, there exists an optimal sequential and finite R&D program (see chapter 5.3).

3.3 The Social Planner's Problem

The decision-maker's problem is therefore characterized by two linkages between the innovation and pollution policy: Firstly, the past history of R&D determines the planner's current degrees of freedom in allocating production to different technologies. Secondly, depending on research success regarding the backstop, additional R&D may optimally be undertaken or not.

The solution to the social planner's problem involves characterizing the control processes of production quantities and R&D timing given the state processes of stock dynamics. The heuristic strategy involves separating the problems into an optimal pollution policy given the number and type of technologies already developed and the optimal R&D policy that determines the extension of the set of technologies at any given point in time. The problem is then

$$\begin{aligned}
\max_{\{q_i(t)\},\{t_2,t_3,\ldots,t_N\},\{N\}} &= \int_0^{t_2} e^{-rt}\left[\left(q_1 - \frac{d_1}{2}S_1^2\right)\right] dt - e^{-rt_2}R \\
&+ p\int_{t_2}^{\infty} e^{-rt}\left[\sum_{i=1}^{2}\left(q_i - \frac{d_i}{2}S_i^2\right)\right] dt \\
&+ (1-p)\left\{\int_{t_2}^{t_3} e^{-rt}\left[\sum_{i=1}^{2}\left(q_i - \frac{d}{2}S_i^2\right)\right] dt - e^{-rt_3}R\right. \\
&+ p\int_{t3}^{\infty} e^{-rt}\left[\sum_{i=1}^{3}\left(q_i - \frac{d_i}{2}S_i^2\right)\right] dt \\
&+ (1-p)\left\{\int_{t_3}^{t_4} e^{-rt}\left[\sum_{i=1}^{3}\left(q_i - \frac{d}{2}S_i^2\right)\right] dt - e^{-rt_4}R\right. \\
&+ p\ldots \\
&+ (1-p)\left.\left.\int_{t_N}^{\infty} e^{-rt}\left[\sum_{i=1}^{N}\left(q_i - \frac{d}{2}S_i^2\right)\right] dt\right\}\ldots\right\}, \qquad (3.7)
\end{aligned}$$

subject to conditions (3.1), (3.4) and (3.5).

To sum up, the nature of the planner's problem describes a situation in which the choices of pollution policy and R&D policy are linked in two ways. Firstly, the past history of R&D determines the planner's current degrees of freedom in allocating production shares to different technologies. Secondly, depending on research success regarding the backstop, additional R&D may optimally be undertaken or not.

Chapter 4

The Optimal Pollution Policy

4.1 The First Order Conditions

With uncertainty only entering at instants of innovation, the optimal pollution policy *between* any two innovation events is a standard deterministic Markov-process where the number of state variables equals the number of available technologies. Conditional on the number and type of technologies and the pollution stocks at the beginning of the considered planning period, the optimal policy can be derived. This is done in this chapter while the optimal R&D policy is studied in chapter 5. Note that while studying the optimal pollution policy the number of technologies remains fixed at $n = n(t_i)$ for all $t \in [t_i, t_{i+1})$, $i = \{1, ..., N\}$, where $t_1 = 0$ is the arrival time of the first (free) technology.

Before deriving the optimal pollution policy, two observations are made regarding the optimal pollution and *post*-backstop R&D policy that greatly simplify the subsequent analysis. The first is that with a perfectly clean technology at hand, it will be used to the capacity limit while output of all polluting technologies is zero. Second, if a backstop is developed no further innovation takes place. Given the model's specification both statements are intuitive and easy to prove.

Given the number of technologies n, the Hamiltonian of problem (3.7) is

$$
\begin{aligned}
H_n \;=\; & \sum_{j=2}^{n}\left[p(1-p)^{j-2}e^{-rt}W^{Back_j}(t)\right]+(1-p)^{n-1}e^{-rt}W^{Boom_n}(t) \\
& +\sum_{j=2}^{n}\left\{p(1-p)^{j-2}\sum_{i=1}^{j}\left[\mu_i^{Back_j}(t)\left(\alpha_i q_i^{Back_j}-\delta_i S_i^{Back_j}\right)\right]\right\} \\
& +(1-p)^{n-1}\sum_{i=1}^{n}\left[\mu_i^{Boom_n}(t)\left(\alpha q_i^{Boom_n}-\delta S_i^{Boom_n}\right)\right] \\
& +\sum_{j=2}^{n}\left[p(1-p)^{j-2}e^{-rt}\kappa^{Back_j}(t)\left(1-\sum_{i=1}^{n}q_i^{Back_j}(t)\right)\right] \\
& +(1-p)^{n-1}e^{-rt}\kappa^{Boom_n}(t)\left(1-\sum_{i=1}^{n}q_i^{Boom_n}(t)\right),
\end{aligned}
$$

where $W^{Back_j}(t)$ is instantaneous welfare given technology j is a backstop and hence j is the size of the technology portfolio and $W^{Boom_n}(t)$ is instantaneous welfare given all n technologies are of the boomerang type. The same notational conventions apply to the shadow prices of pollution stocks, μ, and the shadow prices of the output constraint, κ.

The corresponding first order conditions yield

$$
\begin{aligned}
e^{-rt}+\alpha\mu_i^{Boom_n}(t)-e^{-rt}\kappa^{Boom_n}(t) &= 0, &\quad (4.1)\\
e^{-rt}dS_i^{Boom_n}(t)+\delta\mu_i^{Boom_n}(t) &= \dot{\mu}_i^{Boom_n}, &\quad (4.2)
\end{aligned}
$$

that together with the transversality condition

$$
\lim_{t\to\infty} H_N^*(t)=0, \qquad (4.3)
$$

where H_N^* is the maximized Hamiltonian, determine the optimal pollution policy. Note that (4.1) holds only along the singular path and therefore gives rise to the following switching function (Spence and Starrett 1975)

$$
\sigma_i(t)=e^{-rt}+\alpha\mu_i^{Boom_n}(t)-e^{-rt}\kappa^{Boom_n}(t)\begin{cases} <0 & \Rightarrow\quad q_i^{Boom_n}(t)=0\\ =0 & \Rightarrow\quad q_i^{Boom_n}(t)=q_i^{Boom_n^*}(t)\\ >0 & \Rightarrow\quad q_i^{Boom_n}(t)=1\end{cases} \qquad (4.4)
$$

The pollution policy is more complex in the case where only technologies of the boomerang type are available than in a situation with a backstop. Depending on pollution stocks, three relevant cases require consideration: Case (a) features pollution stocks that are symmetric across all technologies. This is the singular case presented in section 4.2. Case (b) is characterized by one technology initially having a zero stock while the stocks of all other technologies are symmetric and positive. This is a non-singular case presented in section 4.3. Finally, we consider another non-singular case (c) with one technology initially at a zero pollution stock while the stocks of other technologies are at different positive levels (see section 4.4). This selection is exhaustive because by assumption new technologies always start with a zero pollution stock. Case (a) describes the case before the first innovation and after convergence of new and incumbent technologies. If innovation occurs while the economy is in phase (a), then case (b) is relevant. However, if the economy is in phase (b) or (c) when innovation occurs, then case (c) applies.

4.2 The Singular Solution

The singular solution holds for all technologies for which the switching function (4.4) is zero

$$\sigma_i(t) = 0. \tag{4.5}$$

Symmetric stock levels are required for the switching function to be zero for more than one technology. On the singular path, all technologies will obey the following shadow price dynamics

$$\mu_i^{Boom_n}(t) = \frac{e^{-rt}}{\alpha}\left(\kappa_n(t) - 1\right), \tag{4.6}$$

$$\dot{\mu}_i^{Boom_n}(t) = -\frac{e^{-rt}}{\alpha}\left[r\left(\kappa_n(t) - 1\right) - \dot{\kappa}_n(t)\right]. \tag{4.7}$$

Three cases have to be considered:[1]

Case 1: $\kappa_n = 0$ and $\dot{\kappa}_n = 0$

Case 2: $\kappa_n > 0$ and $\dot{\kappa}_n = 0$

Case 3: $\kappa_n > 0$ and $\dot{\kappa}_n \neq 0$

Case 1

In this case, production does not exhaust the capacity constraint (3.4). The constraint is therefore not binding ($\kappa_n = 0$). Using the first order condition (4.2) and the shadow price dynamics (4.6) and (4.7) we obtain

$$S_i^{Boom_n^*}(t) = \frac{r+\delta}{\alpha d}, \tag{4.8}$$

$$q_i^{Boom_n^*}(t) = \frac{\delta(r+\delta)}{\alpha^2 d}, \tag{4.9}$$

[1]These are the relevant cases because κ_n can not become negative in this problem.

with the superscript *Boom* denoting output levels when no backstop is available. The steady state defined in case 1 is "incomplete" in the sense that the marginal damage of pollution outweighs the marginal benefit of production before the capacity constraint becomes binding. Output and stock levels of the incomplete steady state depend positively on the discount rate and negatively on the rate of pollution decay, the accumulation coefficient and the marginal damages of pollution. In case 1, equilibrium output and pollution stock of technologies do not depend on the number of technologies. However, the existence of the 'incomplete' steady state requires that

$$n\frac{\delta(r+\delta)}{\alpha^2 d} \leq 1, \tag{4.10}$$

which is a function of n. For each set of exogenous parameters thus, there is an upper bound of n above which the incomplete steady state is not feasible.

Case 2

Here, the steady state is 'complete': The capacity constraint (3.4) is binding ($\kappa_n > 0$) at a constant corresponding shadow price ($\dot{\kappa}_n = 0$). Again, using the symmetry assumptions, (4.2), (4.6) and (4.7), we find

$$S_i^{Boom_n^*}(t) = \frac{\alpha}{\delta n}, \tag{4.11}$$

$$q_i^{Boom_n^*}(t) = \frac{1}{n}. \tag{4.12}$$

The number of available technologies uniquely determines equilibrium output, with the steady state pollution stocks a function of the accumulation coefficient α, the depreciation rate of pollution δ and the number of technologies. The discount rate r and the slope of the damage function d do not affect the steady state. Existence of the 'complete' steady state requires that

$$n\frac{\delta(r+\delta)}{\alpha^2 d} > 1. \tag{4.13}$$

Note, that (4.10) and (4.13) are mutually exclusive and exhaustive.

Case 3

This case is characterized by a binding capacity constraint ($\kappa^{Boom_n} > 0$) and a changing shadow price of the capacity constraint. Case 3 is therefore not a steady state. Using symmetry and (4.2), (4.6) and (4.7) we find

$$S_i^{Boom_n^*}(t) = \frac{\alpha}{\delta n} - \frac{\alpha}{\delta n}e^{-\delta t}, \tag{4.14}$$

$$q_i^{Boom_n^*}(t) = \frac{1}{n}. \tag{4.15}$$

These conditions define a most rapid approach path to a steady state where all technologies have equal initial pollution stocks. In $t = 0$ the economy has to be in this case because by assumption $n(0) = 1$ and $S_1(0) = 0$.[2] As stocks accumulate according to (4.14) and no innovation occurs, the economy either reaches the incomplete steady state (Case 1) or approaches the complete steady state (Case 2). Which steady state is relevant is determined by conditions (4.10) and (4.13).

4.3 Innovation with Symmetric Stocks

The analysis of the singular case restricts attention to situations with symmetric pollution stocks across all technologies. Obviously, in the event of an innovation at some point in time $t_n > 0$, this restriction cannot apply: While the incumbent technologies $\{1, ..., n-1\}$ have already accumulated some stock, that of the new one, n, is still zero. As pollution stocks differ across new and established technologies, so will their respective shadow prices. Assume that this is the first innovation at some strictly positive point in time (though, it will be shown later that the analysis also applies to all subsequent innovations). When a boomerang is developed the pollution stocks are

$$S_i^{Boom_n^*}(t_n) = \frac{\alpha}{\delta(n-1)} - \frac{\alpha}{\delta(n-1)} e^{-\delta t_n}, \quad i = 1, ..., n-1, \tag{4.16}$$

$$S_n^{Boom_n^*}(t_n) = 0. \tag{4.17}$$

Here, the singular condition (4.5) cannot hold for all technologies simultaneously but only for one of the two sets of technologies. Since $S_i^{Boom_n^*}(t_n) > S_n^{Boom_n^*}(t_n)$ and therefore $\mu_i^{Boom_n}(t_n) < \mu_n^{Boom_n}(t_n)$ it has to hold that $\sigma_i(t_n) < \sigma_n(t_n)$. Due to (3.4), (4.5) can only hold for the new technology while for all $n-1$ old technologies $\sigma_i(t_n) < 0$ and hence

$$q_i^{Boom_n^*}(t) = 0, \quad \forall t \in \left[t_n, \hat{t}_n\right], \quad i = 1, ..., n-1, \tag{4.18}$$

$$q_n^{Boom_n^*}(t) = 1, \quad \forall t \in \left[t_n, \hat{t}_n\right]. \tag{4.19}$$

These conditions define the most rapid approach path to a situation where pollution stocks of all technologies are equal. The corresponding stock dynamics are

$$S_i^{Boom_n^*}(t) = S_i^{Boom_n^*}(t_n) e^{-\delta(t-t_n)}, \quad \forall t \in \left[t_n, \hat{t}_n\right], \tag{4.20}$$

$$S_n^{Boom_n^*}(t) = \frac{\alpha}{\delta} - \frac{\alpha}{\delta} e^{-\delta(t-t_n)}, \quad \forall t \in \left[t_n, \hat{t}_n\right], \tag{4.21}$$

[2] The same holds for $n(0) > 1$. Since for all $i \in \{1, ..., n(0)\}$ it holds that $S_i^{Boom_n}(0) = 0$.

where $\hat{t}_n$ is the point in time where $S_i^{Boom_n^*}(\hat{t}_n) = S_n^{Boom_n^*}(\hat{t}_n)$. Using (4.20) and (4.21) the point of convergence is at

$$\hat{t}_n = t_n + \frac{1}{\delta} \ln \left[\frac{\delta}{\alpha} S_i^{Boom_n^*}(t_n) + 1 \right]. \tag{4.22}$$

Between $\hat{t}_n$ and the next innovation, all technologies are used in equal amounts. Their stocks grow according to the 'Case 3'-process

$$S_l^{Boom_n^*}(t) = \frac{\alpha}{\delta n} - \frac{\alpha}{\delta n} e^{-\delta(t-\bar{t}_n)}, \quad t > \hat{t}_n, l = 1, ..., n. \tag{4.23}$$

This process has a virtual starting point, $\bar{t}_n$, determined by

$$S_l^{Boom_n^*}(\hat{t}_n) = S_i^{Boom_n^*}(\hat{t}_n), \quad i = 1, ..., n-1, l = 1, ..., n, \tag{4.24}$$

which yields

$$\bar{t}_n = 0. \tag{4.25}$$

The path of the pollution stock after innovation and convergence (4.23) is therefore identical to the one where all n technologies are available at $t = 0$ (4.14). The process of analyzing the subsequent arrival of boomerang technologies is therefore analogous, by substituting in the respective new value for n. This analogy hinges, however, on the condition that innovation takes places after convergence. The following section (c) analyzes the alternative case.

4.4 Innovation with Asymmetric Stocks

Here, a boomerang technology arrives at $t_n \in \{t_{n-1}, \hat{t}_{n-1}\}$ prior to pollution stocks of technologies $\{1, ..., n-1\}$ having converged. Again, the most rapid approach path is optimal, i.e.

$$q_i^{Boom_n^*}(t) = 0, \quad \forall t \in \left[t_n, \hat{t}_n\right], \quad i = 1, ..., n-1, \tag{4.26}$$

$$q_n^{Boom_n^*}(t) = 1, \quad \forall t \in \left[t_n, \hat{t}_n\right]. \tag{4.27}$$

Applying the same heuristics as above for deriving $\hat{t}_n$, the point in time at which convergence of the stocks of technologies $n-1$ and n occurs is

$$\hat{t}_n = t_n + \frac{1}{\delta} \ln \left[\frac{\delta}{\alpha} S_i^{Boom_n^*}(t_n) + 1 \right]. \tag{4.28}$$

It is a question of the optimal timing of R&D whether or not this case ever arises. This question is addressed in the following chapter. For this, it is useful to note that asymmetric stocks do not affect the optimal pollution policy after the development of a backstop technology.

Chapter 5

The Optimal Timing of R&D

5.1 Setup of the Optimal Timing Decision for R&D

The previous chapter derived the optimal contingent pollution policies. Given these policies, the social planner faces the problem at which points in time to invest into R&D and thereby acquire a new technology that can turn out to be either of the backstop or the boomerang type.

The following analysis is based on recent results on multi-stage dynamic optimization techniques derived by Makris (2001) and Tomiyama (1985). The application of the technique to the problem at hand is natural: Here, a *stage* is defined by reference to the number n of technologies available for production. Switching between stages n and $n+1$ involves carrying out R&D at cost R. While the necessary conditions derived by Tomiyama (1985) and Makris (2001) are established in the context of a deterministic setting, they are easily modified for the simple discrete probability distribution studied here in order to account for the uncertainty regarding the type of technology developed at the point of switching.

Given the initial endowment of $n(0) = 1$ technologies the optimization problem is as follows

$$\max_{\{t_2,t_3,...,t_N\},\{N\}} J = \int_0^{t_2} e^{-rt}\left[\left(q_1^{Boom_1^*} - \frac{d}{2}(S_1^{Boom_1^*})^2\right)\right] dt - e^{-rt_2}R$$
$$+ (1-p)\left\{\int_{t_2}^{t_3} e^{-rt}\left[\sum_{i=1}^{2}\left(q_i^{Boom_2^*} - \frac{d}{2}(S_i^{Boom_2^*})^2\right)\right] dt - e^{-rt_3}R\right\}$$
$$+ p\left\{\int_{t_2}^{\infty} e^{-rt}\left[\sum_{i=1}^{2}\left(q_i^{Back_2^*} - \frac{d_i}{2}(S_i^{Back_2^*})^2\right)\right] dt\right\}$$
$$+ \dots$$
$$+ (1-p)^{N-1}\int_{t_N}^{\infty} e^{-rt}\left[\sum_{i=1}^{N}\left(q_i^{Boom_n^*} - \frac{d}{2}(S_i^{Boom_n^*})^2\right)\right] dt$$
$$+ p(1-p)^{N-2}\int_{t_N}^{\infty} e^{-rt}\left[\sum_{i=1}^{N}\left(q_i^{Back_n^*} - \frac{d_i}{2}(S_i^{Back_n^*})^2\right)\right] dt, \quad (5.1)$$

subject to (3.1) and (3.4). This is equivalent to (3.7) with the exception that the optimal pollution policy has already been solved and that the path probabilities (see Figure 3.1) have been multiplied out. The corresponding Hamiltonian for each stage, where n technologies already exist, is

$$\begin{aligned} H_n \;=\; & \sum_{j=2}^{n}\left[p(1-p)^{j-2}e^{-rt}W^{Back_j^*}(t)\right] + (1-p)^{n-1}e^{-rt}W^{Boom_n^*}(t) \\ & + \sum_{j=2}^{n}\left\{p(1-p)^{j-2}\sum_{i=1}^{j}\left[\mu_i^{Back_j}(t)\left(\alpha_i q_i^{Back_j^*} - \delta_i S_i^{Back_j^*}\right)\right]\right\} \qquad (5.2) \\ & + (1-p)^{n-1}\sum_{i=1}^{n}\left[\mu_i^{Boom_n}(t)\left(\alpha q_i^{Boom_n^*} - \delta S_i^{Boom_n^*}\right)\right], \quad n = 1, ..., N. \end{aligned}$$

Given the optimal pollution policies, the applicable necessary conditions for the optimal switching point are essentially those provided by Tomiyama (1985) and Makris (2001). However, since there is uncertainty about the type of the technology developed, they are modified accordingly (proof see appendix). Two conditions then determine the optimal instant t_{n+1}^* to undertake R&D in order to develop the $n+1^{st}$ technology. The first is a *matching condition* that requires that - in expected terms - the pollution shadow prices of existing technologies are continuous at the switching instant, i.e.

$$\mu_i^{Boom_n^*}(t_{n+1}^*) = E\left(\check{\mu}_i^*(t_{n+1}^*)\right), \quad i = 1, ..., n, \qquad (5.3)$$

where $\mu_i^{Boom_n^*}(t_{n+1}^*)$ is the shadow price of stock i at t_{n+1}^* with n boomerang technologies while $E\left(\check{\mu}_i^*(t_{n+1}^*)\right) = p\mu_i^{Back_{n+1}^*}(t_{n+1}^*) + (1-p)\mu_i^{Boom_{n+1}^*}(t_{n+1}^*)$ is the expected shadow price of the same stock at the switching instant but 'after' innovation given that optimal pollution policies are implemented. The shadow prices of pollution stocks depend on the optimal pollution policy. Since the latter is conditional on the type of technology developed, so are the shadow prices. Hence the matching condition of Tomiyama (1985) and Makris (2001) for the deterministic case ($\mu_i = \breve{\mu}_i$) must hold in expected terms.

The second condition is the *research arbitrage condition*

$$\sum_{n=1}^{N-1} \left\{ \left[H_n^* \left(t_{n+1} \right) + (1-p)^{n-1} e^{-rt_{n+1}} rR - H_{n+1}^* \left(t_{n+1} \right) \right] \delta t_{n+1} \right\} \leq 0, \qquad (5.4)$$

for any admissible perturbation δt_{n+1} in the innovation time t_{n+1}^*.

Using both necessary conditions and substituting in the optimal pollution policies this yields (proof see appendix)

$$rR \leq \alpha \left[E\left(\breve{\mu}_{n+1}^* \left(t_{n+1}^* \right) \right) - E\left(\breve{\mu}_n^* \left(t_{n+1}^* \right) \right) \right] e^{rt_{n+1}^*}, \quad t_{n+1}^* = 0, \qquad (5.5)$$

$$rR = \alpha \left[E\left(\breve{\mu}_{n+1}^* \left(t_{n+1}^* \right) \right) - E\left(\breve{\mu}_n^* \left(t_{n+1}^* \right) \right) \right] e^{rt_{n+1}^*}, \quad t_{n+1}^* > 0, \qquad (5.6)$$

for the $n+1^{st}$ technology developed at instant t_{n+1}^*. The optimal time to innovate is when the marginal gain of waiting (the left hand sides) is not higher than the expected marginal cost of doing so (the right hand sides). The latter is determined by the difference between the expected shadow price of the new technology ($E\left(\breve{\mu}_{n+1}^*\right)$) and that of the lowest pollution stock of an active technology ($E\left(\breve{\mu}_n^*\right)$.

5.2 Characterization of the Optimal Innovation Policy

Here the key results on the optimal innovation policy are presented. The emphasis is on developing the essential heuristic steps for characterizing the optimal policy, with some of the algebraic manipulation relegated to the appendix where indicated.

Proposition 5.1 *There is no upfront innovation at the beginning of the planning period ($t = 0$).*

Proof. At $t = 0$, the existing as well as any newly developed technology have - by definition - a pollution stock of $S_i(0) = 0$. If research produces a boomerang technology it is perfectly symmetric to any already existing one. Hence, the shadow prices are the same in this case: $\mu_1^{Boom_2^*}(0) = \mu_2^{Boom_2^*}(0)$. If research produces a backstop technology instead, the shadow price of the perfectly clean technology is zero ($\mu_2^{Back_2}(0) = 0$). The shadow price of any polluting technology at the instant a backstop arrives is given by (see appendix)

$$\mu_i^{Back_{n+1}} \left(t_{n+1}^* \right) = -\frac{d}{r+2\delta} S_i^{Boom_n} \left(t_{n+1}^* \right) e^{-rt_{n+1}^*}, \quad i = 1, ..., n. \qquad (5.7)$$

At the beginning of the planning horizon all pollution stocks are zero and hence $\mu_2^{Back_2}(0) = 0$. Hence, the expected shadow prices of both the initially freely available and any newly developed technology at $t = 0$ are the same: $E\left(\check{\mu}_2^*(0)\right) = E\left(\check{\mu}_1^*(0)\right)$. Plugging this into (5.5) yields that there is no research upfront if R&D is costly ($R > 0$) and the social planner not infinitely patient ($r > 0$). $\square$

Proposition 5.2 *Innovation is sequential. At most one technology is developed at any point in time.*

This property of the optimal R&D trajectory has been assumed to hold throughout chapter 4 and the previous section in order to simplify the presentation. In appendix A.4 it is proved that this is indeed optimal.

More detail about the optimal timing of research is obtained by replacing the expected shadow prices in (5.6) with more explicit terms. First, rewrite (5.6) using $\mu_{n+1}^{Back_{n+1}} = 0$ as follows

$$\begin{aligned} rR = \alpha \Big\{ &(1-p)\mu_{n+1}^{Boom_{n+1}}\left(t_{n+1}^*\right) \\ &- \left[p\mu_n^{Back_{n+1}}\left(t_{n+1}^*\right) + (1-p)\mu_n^{Boom_{n+1}}\left(t_{n+1}^*\right)\right]\Big\} e^{rt_{n+1}^*}, \quad t_{n+1}^* > 0. \end{aligned} \tag{5.8}$$

$\mu_n^{Back_{n+1}}\left(t_{n+1}^*\right)$ is given by (5.7). Note that there is a link between $\mu_{n+1}^{Boom_{n+1}}\left(t_{n+1}^*\right)$ and $\mu_n^{Boom_{n+1}}\left(t_{n+1}^*\right)$: Assuming the stocks of both boomerang technologies converge at some point in time (this assumption is shown to be correct in Proposition 5.3), technologies are at that point perfectly symmetric with respect to their exogenous parameters, stocks and optimal future pollution policies. Hence, at the point of convergence shadow prices of both technologies are the same. Using this link, it is possible to express one shadow price in terms of the other. Given the optimality of most rapid convergence except in the case of further innovations occurring in the meantime (see (4.18) and (4.19)), the relation is as follows (proof see appendix)

$$\begin{aligned} \mu_{n+1}^{Boom_{n+1}}(t_{n+1}^*) = \mu_n^{Boom_{n+1}}\left(t_{n+1}^*\right) + de^{-rt_{n+1}^*} \Bigg\{ &\frac{S_n^{Boom_n^*}\left(t_{n+1}^*\right)}{r+2\delta} \\ &- \frac{\alpha}{(r+\delta)(r+2\delta)}\left[1 - \left(\frac{\delta}{\alpha} S_n^{Boom_n^*}\left(t_{n+1}^*\right) + 1\right)^{-\frac{r+\delta}{\delta}}\right]\Bigg\}. \end{aligned} \tag{5.9}$$

Substituting (5.7) and (5.9) into (5.8) yields the *research trigger condition*

$$rR = \frac{\alpha d}{r+2\delta} S_n^{Boom_n^*}\left(t_{n+1}^*\right) - \frac{(1-p)\alpha^2 d}{(r+\delta)(r+2\delta)}\left[1 - \left(\frac{\delta}{\alpha} S_n^{Boom_n^*}\left(t_{n+1}^*\right) + 1\right)^{-\frac{r+\delta}{\delta}}\right]. \tag{5.10}$$

This determines the optimal switching times $t_1^*, ..., t_N^*$ and thereby the optimal number of technologies N if innovation occurs only when the pollution stocks of all existing technologies have converged. Hence, the next issue is to proof that this is indeed the case.

Proposition 5.3 *Innovation occurs only at instances at which all available technologies are used simultaneously.*

Proof. For any given interval $[t^1, t^2]$ during which no innovation occurs, the gains from innovation are monotonically increasing in the stock of the most recent technology and hence in time. Note that at the instant a technology is developed the gains of further innovation are zero. As the pollution stock of the most recent technology accumulates, gains from innovation increase. The costs of research, on the other hand, are constant. The single crossing property of this setting determines the research trigger condition (5.10) as the unique optimal switching point. (5.10) requires all existing technologies to be used simultaneously. Innovation during convergence is therefore ruled out. □

(5.10) therefore fully characterizes the optimal R&D sequence in this stylized model.

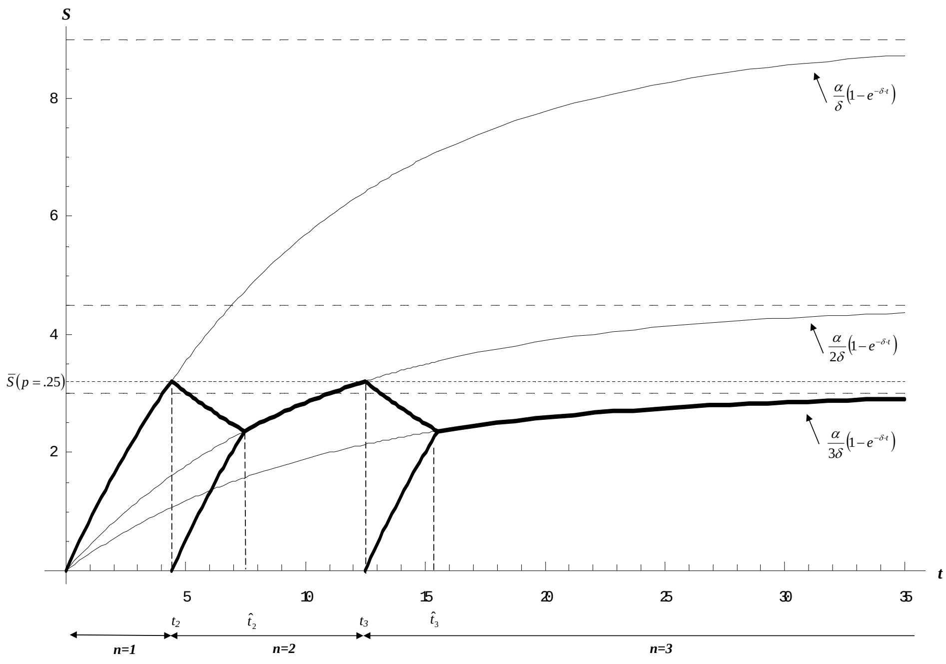

Figure 5.1: Optimal evolution of stock and R&D sequence (*N=3*) when R&D fails to develop a backstop ($p = 0.25$).

Together with the optimal pollution policies derived in chapter 4 the optimal joint pollution and R&D program is determined. A specific representation for the corresponding evolution of pollution stocks is given in Figure 5.1. It depicts a situation with $N = 3$ where - by construction - no backstop arrives. While the actual equilibrium stocks are represented by bold lines, the fine (solid) lines are the approach paths to the steady states given 1, 2 or 3 technologies, respectively. Note that since the capacity constraint is always binding and technologies of the boomerang type are symmetric, the approach path to the steady state given one technology is active is also the evolution of the total aggregate pollution stock. Due to (3.2) this is not proportional to aggregate damages in the economy. The dashed horizontal lines indicate the (hypothetical) steady state levels for $n = 1$, $n = 2$ and $n = 3$. Based on (5.10), one can say more about the exact link between pollution (stocks) and R&D.

Proposition 5.4 *In the optimum innovation occurs whenever the pollution stock of any technology reaches a constant threshold level $\bar{S}$.*

Proof. Time enters the research trigger condition (5.10) only via the pollution stock of the most recent technology. Since all other variables in (5.10) are exogenous parameters, research is triggered each time $S_n^{Boom_n^*}\left(t_{n+1}^*\right) = \bar{S}$. Moreover, since all pollution stocks are symmetric in all switching instants (Proposition 5.3) this is equivalent to any pollution stock reaching the trigger level $\bar{S}$. $\square$

The dotted horizontal line in Figure 5.1 indicates this pollution threshold level. Having established this tight relation between pollution stocks and the timing of innovation, one is now in a position to state some further properties of the optimal R&D and pollution trajectories. One important feature is the optimal procedure if R&D (repeatedly) fails to deliver the desired backstop technology. The question here is whether research is carried out - potentially *ad infinitum* - until a backstop is developed or whether R&D eventually ceases even if the pollution problem has not been solved.

Proposition 5.5 *The optimal R&D program has an endogenous stopping point. For any set of parameters with $R > 0$ and $r > 0$, at most $N = \min[\hat{N}, M]$ technologies are developed. $\hat{N}$ is independent of the maximum number of feasible technologies, M.*

Proof. Innovation ceases if a backstop technology is developed. If no backstop arrives (either because $p = 0$ or because of bad luck) there is an upper bound on the number of boomerang technologies developed in the optimum. To see this, recall that the steady state pollution stock (4.11) is strictly decreasing in the number of available technologies n. Moreover, $\lim_{n\to\infty} \frac{\alpha}{\delta n} = 0$. Hence, there is a number of boomerang technologies $\hat{N}$ for which the condition $\frac{\alpha}{\delta \hat{N}} < \bar{S} \leq \frac{\alpha}{\delta(\hat{N}-1)}$ holds. Once the $\hat{N}^{th}$ boomerang is developed, the innovation trigger level will not be reached again. Given that $M \geq \hat{N}$ and since p is independent of both M and n, the size of the set of feasible technologies, M, does not affect the maximum number of technologies, N, developed in an optimal R&D program. □

The optimal stopping rule for R&D is therefore as follows: no further R&D is carried out if either a backstop arrives or $N = \min[\hat{N}, M]$ boomerang technologies have been developed. R&D stops even though a backstop may not have been developed and even though there are still potential technological solutions to be discovered. This pattern of R&D timing has repercussions on the optimal evolution of pollution stocks.

Proposition 5.6 *If and only if the optimal R&D policy requires at least one innovation and M is not binding (i.e. $1 \leq \hat{N} \leq M$), pollution stocks overshoot.*

Proof. Each time innovation occurs all pollution stocks are at $\bar{S}$ (Propositions 5.3 and 5.4). If a backstop is developed, pollution stocks will fall and approach zero in the long run. This is a trivial form of overshooting. If no backstop is developed, then the economy has N boomerang technologies in the long run (Proposition 5.5). If $M \geq \hat{N}$, the corresponding steady state level of pollution stocks is below the innovation trigger level, each time innovation occurs pollution stocks of all available technologies are above their long run steady state level. Overshooting occurs whether a backstop arrives in the future or not. However, if it is never optimal to undertake R&D, i.e. if $\frac{\alpha}{\delta} \leq \bar{S}$, the pollution stock of the only available technology never exceeds its long run steady state. The same holds if $M < \hat{N}$ and the sequence of innovations stops because the set of potential ideas to solve the pollution problem is exhausted. In this case the long run steady state is above the innovation trigger level, but no R&D occurs because the economy is short of new ideas. □

Proposition 5.6 implies that, even if there is a specific long run pollution target (say for the carbon dioxide concentration in the atmosphere), it can be optimal to exceed this level for some (repeated) periods of time.[1] Moreover, both the periods when stocks overshoot as well as the time between two such periods increases in the number of available boomerang technologies.

[1] Note that this model abstracts from irreversible catastrophic damages triggered at specific stock levels.

Proposition 5.7 *The time between successive innovations is increasing in the number of already available technologies.*

Proof. After a new technology is developed pollution stocks converge. This process takes $\hat{t}_{n+1} - t_{n+1}$. According to (4.22) the length of this period is independent of the number of technologies already available. The next innovation is triggered if all pollution stocks simultaneously reach $\bar{S}$ again. Since after convergence is completed all technologies are used at a rate of $1/(n+1)$, which is decreasing in n, the time that passes between successive innovations increases in n. □

Although there is no upfront innovation (Proposition 5.1) the R&D program is front loaded in a sense that the 'density' of innovations, i.e. the number of innovations within a given but sufficiently large interval of time, is decreasing in time.

5.3 No Backstop is Feasible

How does the optimal R&D program look like if no backstop technology is feasible, i.e. if $p = 0$? In this case, where research always yields a boomerang technology, there is only one reason to carry out R&D: the differentiation of the pollution portfolio in order to exploit the fact that marginal damages are increasing in each stock but additive across them. The question arises whether the absence of the second driver of innovation, the hope to solve the pollution problem once and for all, has a qualitative impact on the optimal pollution policy and research trajectory.

First note that the optimal pollution policy presented in chapter 4 remains valid, since it was derived given that only boomerang technologies are available. Moreover, it is independent of the probability to develop a backstop p. However, the social planner's problem is no longer stochastic since in this special case there is no technological uncertainty. The corresponding first order conditions are the ones derived by Makris (2001) without any adjustments for uncertainty at the switching instances. The research trigger condition 5.10 therefore simplifies to

$$rR = \frac{\alpha d}{r+2\delta} S_n^{Boom_n^*}\left(t_{n+1}^*\right) - \frac{\alpha^2 d}{(r+\delta)(r+2\delta)}\left[1 - \left(\frac{\delta}{\alpha} S_n^{Boom_n^*}\left(t_{n+1}^*\right) + 1\right)^{-\frac{r+\delta}{\delta}}\right]. \tag{5.11}$$

Compared to the case with a strictly positive p, the threshold pollution stock that triggers R&D is higher if no backstop is feasible. Hence, research occurs later and is less frequent when there is no chance to escape from the pollution problem. However, the overall pattern of the optimal R&D program remains unchanged. Propositions 5.1 - 5.7 are valid for a situation where no backstop technology is feasible (Goeschl and Perino 2007c).

5.4 The Effects of Technological Uncertainty

So far the probability of a backstop to arrive by virtue of R&D did not affect the validity of any of the previous propositions. However, it is an important determinant of the optimal timing of research.

Proposition 5.8 *The maximum number of technologies developed, N, is weakly increasing in the probability, p, that a backstop is developed by R&D. The time between successive innovations is strictly decreasing in p.*

Proof. Making use of the property that $S_n^{Boom_n^*}\left(t_{n+1}^*\right) = \bar{S}$ established in Proposition 5.4 and total differentiating (5.10) yields

$$\frac{d\bar{S}}{dp} = -\frac{\alpha}{r+\delta} \cdot \frac{1 - \left[\frac{\delta}{\alpha}\bar{S} + 1\right]^{-\frac{r+\delta}{\delta}}}{1 - (1-p)\left[\frac{\delta}{\alpha}\bar{S} + 1\right]^{-\frac{r+2\delta}{\delta}}} < 0. \tag{5.12}$$

The pollution stock threshold $\bar{S}$ is decreasing in p. However, N is weakly decreasing in $\bar{S}$ (see proof of Proposition 5.5). In addition, the time between successive innovations is increasing in $\bar{S}$ (see Figure 5.1). Both the time interval pollution stocks required to converge (see (4.22)) and the time interval spent rebuilding pollution stocks back to $\bar{S}$ are reduced. □

The intuition behind Proposition 5.8 is straightforward. A backstop technology is always more desirable than a technology of the boomerang type. Increasing the probability that research produces a backstop while keeping the costs of R&D, R, constant, makes research more attractive. It is carried out earlier and potentially more often.

Figure 5.2 illustrates the relation between the probability that research produces a clean backstop and the maximum size of the technology portfolio, N, if M is not binding. The two bold horizontal lines represent the threshold pollution stock $\bar{S}$ for $p = 0$ and $p = 1$, respectively. The range in between covers all feasible threshold levels corresponding to specific probabilities to develop a backstop. Note that the relation between p and $\bar{S}$ is concave (see also (5.12)). A marginal increase of p results in a larger decrease in the threshold if p is small than if it is large. The dots are steady state pollution stocks for a given number of active technologies, n. All

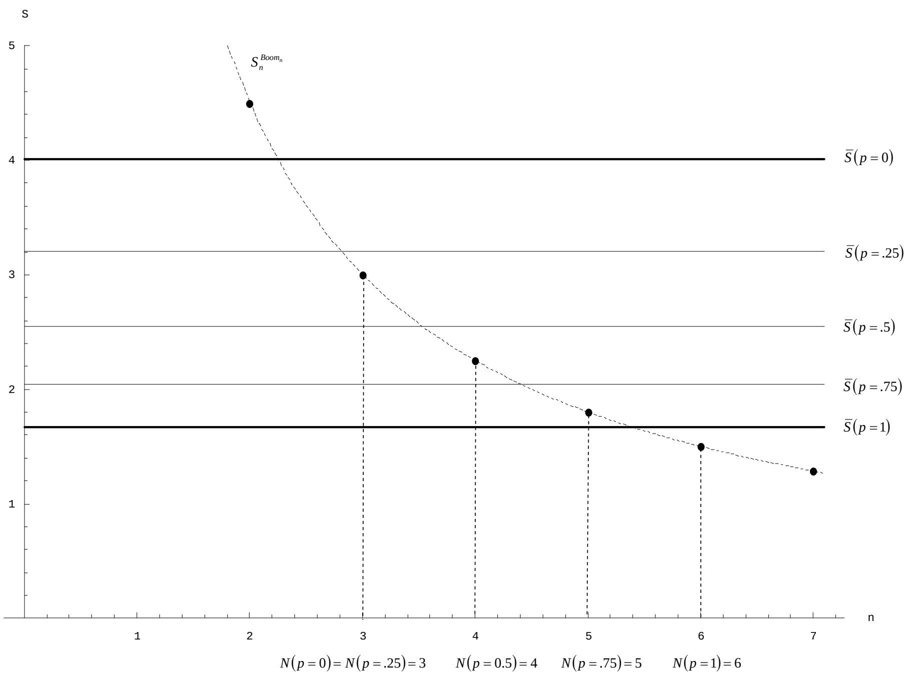

Figure 5.2: The upper bound on the technology portfolio.

dots reside on the dotted hyperbolic line that represents the steady state defined by equation (4.11), $S_n^{Boom_n} = \frac{\alpha}{\delta n}$, if n is not restricted to natural numbers. However, since the number of technologies is always a natural number and M might be binding, the upper bound to the technology portfolio, N, is only weakly increasing in p. In Figure 5.2 this occurs, e.g. when increasing p from zero to 0.25 (the latter appears also in Figure 5.1). In both cases $N = 3$ since it is the largest steady state pollution stock that is below the respective $\bar{S}(p)$.

Figure 5.3 presents three informative characteristics of the optimal R&D program as functions of p. The bold solid line is the maximum number of technologies developed $\hat{N}$. It is weakly increasing in p since an increase in the chance of developing a backstop at each trial increases the expected benefits from R&D. However, the expected number of technologies developed $E(N)$, indicated by the dotted line, is decreasing in general. Exceptions are instances where the maximum number exhibits a discontinuous upward shift. Both the discontinuous jumps in $\hat{N}$ as well as the non-monotonicity in $E(N)$ are due to the restriction of N to the set of integers. The dashed line represents the probability that the optimal R&D program fails to develop a backstop technology at some stage. It is strictly monotonously decreasing in p. Two distinct effects work in the same discretion. If p increases the probability for each R&D project to fail is reduced. Moreover, the maximum number of

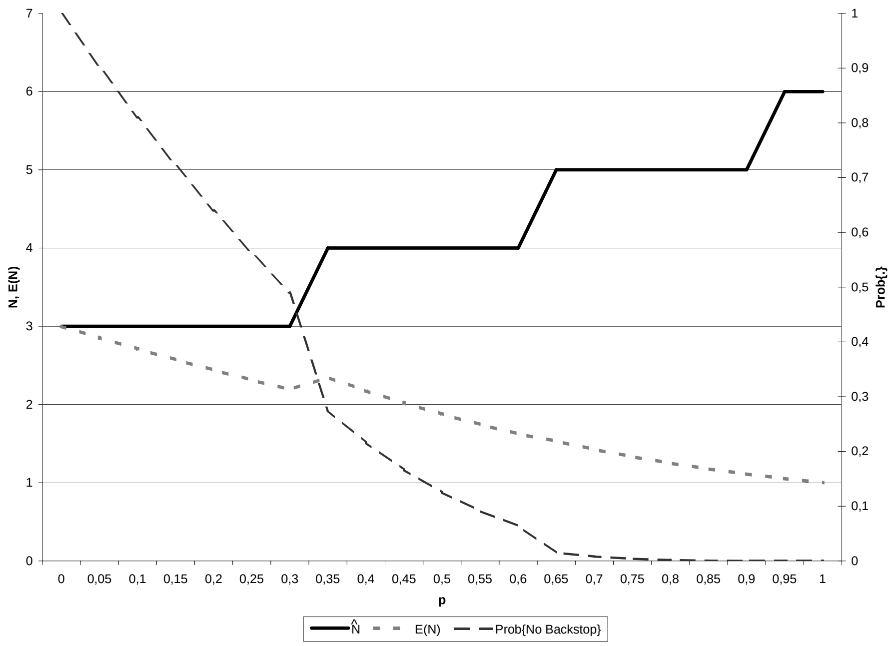

Figure 5.3: Maximum and Expected Number of Innovations and Probability that no Backstop is Developed as Functions of p.

attempts increases as p goes up. For $p = 0.5$ the probability to end up without a backstop is only 12.5%. With $p = 0.75$ it reduces even to 0.39%. Hence, there are large potential gains from increases in the R&D success rate.

5.5 A Short History of Refrigeration

While clearly stylized, key elements of the predicted pattern generated by this model are empirically observable phenomena, in particular the temporary displacement of established technologies by new substitutes, the simultaneous use of different technologies, and a sequential increase in the portfolio of technologies. These phenomena will be most easily observed in settings where users are essentially indifferent about the production technology, justifying the assumption of perfect substitutability, and the technology-specificity of capital is low, thus justifying the assumption of insignificant investment constraints.

As an example, consider the case of refrigeration. Consumers are arguably indifferent about the technological basis of the refrigeration services they consume; and the rate of product replacement for smaller devices is sufficiently high and retrofitting is economical for most existing larger installations (McMullan 2002).

From the 1890s, when refrigeration became commercially viable, several technologies based on different refrigerants competed in this market. The three main competitors were technologies based on ammonia, carbon dioxide and sulphur dioxide, each with specific health and environmental drawbacks. The quest for a safer technology involved such prominent figures as Albert Einstein and Leo Szilard, who jointly invented and patented at least three different cooling technologies, each which its own specific drawbacks (Dannen 1997). In the mid-20th century, the poisonous cooling agents were substituted by CFCs on a large scale. After the ozone depleting effect of CFCs was discovered, three things happened. First, production of CFCs was phased out (Montreal Protocol). Second, the available alternative technologies based on ammonia, carbon dioxide and sulphur dioxide were revived (Pearson 2005). Third, research in and subsequently production of new substitutes such as perfluorocarbons (PFCs) and HCFCs increased. Both PFCs and HCFCs have a considerably lower ozone depleting potential than CFCs. However, both have stock pollution problems of their own: HCFCs decay into trifluoroacetate (TFA) which is toxic and accumulates in harmful amounts in soil and vegetation, necessitating policy intervention in time (Likens et al. 1997). PFCs result in the release of greenhouse gases and therefore contribute to an existing stock pollutant problem. As a result, PFC production is included as a regulatory target in the context of the Kyoto Protocol (McMullan 2002). Hence, despite the highly stylized nature of the model, core features of the predicted pattern arise in in suitable real world settings.

Chapter 6

Extensions

This chapter generalizes the baseline model in several directions. In section 6.1, alternatives to the assumption of time-invariant R&D costs are considered. In section 6.2, the social planner's belief about the probability to develop a backstop is allowed to evolve taking the outcomes of previous R&D efforts into account. In section 6.3, the effects of allowing for generalized welfare and stock accumulation functions are studied. It will turn out that the extensions in these sections differ with respect to their impact on the optimal R&D and pollution policy. All extensions affect the general properties of the R&D arbitrage equation (5.6), with the extensions of the first section affecting its left-hand side and those of the second and third affecting its right-hand side. The general properties of the optimal pollution policy, on the other hand, are unaffected by changes to the assumption on R&D costs. A precise characterization of the effects of generalized R&D processes on the innovation and pollution dynamics in section 6.1 is therefore possible. The same holds for the case of evolving beliefs. Alternative welfare and stock accumulation functions, by contrast, can have a profound impact on the optimal pollution policy. As a result, a complete characterization of pollution and research trajectories in section 6.3 is not possible within the limits of this thesis. Instead, several partial results are offered as building blocks for future research.

6.1 Alternative R&D Processes

In this section, the assumption of time-invariant R&D costs are relaxed to study cases such as an exogenous reduction in research costs over time as well as increasing and decreasing returns to R&D. All have in common that they affect only the left hand side of condition (5.10). Moreover, the optimal pollution policy between innovations remains unaffected and hence, only the specific timing of innovation changes.

6.1.1 Exogenous Efficiency Improvements in Research

Assume that the costs to develop a new technology exogenously decrease over time

$$R = R(t), \quad \text{with } \dot{R} < 0.$$

This can be due to technological progress realized outside of the economy or industry under concern. The cost to acquire a new technology decreases over time and so does the innovation trigger level, $\bar{S}(t_{n+1}) > \bar{S}(t_{n+2})$. Hence, the time between successive innovations does no longer necessarily increase and is certainly shorter than under constant research costs at the same initial level. The steeper the slope of the research cost function the more likely are decreasing intervals between innovations. If the cost decline is sufficiently steep, the trigger level might be reached before technologies have completely converged. In this case Proposition 5.3 ceases to hold. Moreover, if $R(t)$ converges sufficiently fast toward zero, there might be no finite $N \leq M$ where innovation stops. If the assumption of a finite upper bound M on the number of potential innovations is relaxed, the first order condition (5.4) is no longer a necessary condition and theory, so far, offers no guidance on alternative necessary conditions (Makris 2001). While the optimal timing of R&D cannot be established, it is certain that innovation proceeds *ad infinitum*.

6.1.2 Increasing Returns to R&D

Assume, e.g. due to learning by doing, that the costs of R&D decrease with the number of technologies already developed

$$R = R(n), \quad \text{with } \frac{\partial R}{\partial n} < 0. \tag{6.1}$$

According to the same logic as in the previous specification with exogenous cost reductions, innovation occurs earlier than with constant research costs and potentially more technologies are developed. The former is in line with findings by Tsur and Zemel (2003). Propositions 5.2 and 5.6 hold while 5.4, 5.3 and 5.5 do not. Again, the formal analysis is restricted by the lack of a theoretical proof of necessary conditions for optimal control problems with infinite regime switches and an infinite time horizon.

Proposition 6.1 *If the costs of research decrease over time, at least as many technologies are developed than in a situation with similar initial but constant research costs. Innovation might not cease. If it does, research occurs earlier than in a situation with similar initial but constant research costs.*

6.1.3 Decreasing Returns to R&D

Assume the costs of R&D increase with the number of technologies already developed. For example, it may become more and more difficult to find new solutions to the same problem

$$R = R(n), \quad \text{with } \frac{\partial R}{\partial n} > 0. \tag{6.2}$$

Proposition 6.2 *If the costs of research increase in the number of already developed technologies, research occurs later and at most as many technologies are developed than in a situation with similar initial but constant research costs. Innovation neither guarantees overshooting nor production at full capacity in the long run.*

The innovation trigger level increases in the number of technologies already developed, since R is increasing in n. Hence, the time between successive innovation increases compared to the case with similar initial but constant research costs. Propositions 5.2, 5.3 and 5.5 hold while 6.1 does not. Overshooting does not occur if the long run steady state is above the threshold level of the last innovation (otherwise it would not have occurred) but below the new, increased trigger level of the next (not developed) technology. Hence, Proposition 5.6 does not hold. In contrast to the original set-up it is possible that after innovation has occurred the incomplete steady state is reached.

6.2 Evolving Technological Beliefs

So far the analysis was restricted to cases where the probability that a backstop arrives, p, is constant. However, this is not necessarily the case. Depending on the underlying process of picking discoveries out of the pool of feasible ideas the outcome of a R&D project provides information on the expected success rate of future research. This gives rise to endogenously evolving beliefs about the probability to develop a backstop. Two specific evolutions of p are studied. The first is dubbed 'technology optimist', where the social planner believes to know both the number of feasible technologies M as well as the number of backstops BS in this pool of ideas. The second is labeled 'technology pessimist' and it is assumed that while the planner believes to know M, he is aware that his belief on the number of backstops BS is just a guess.

6.2.1 The Technology Optimist

This scenario where both M and BS are believed to be known, matches the well known set up of random draws from an urn without replacement.[1] The two types of balls in the urn are backstops and boomerangs. The probability of drawing a backstop given that all previous n draws produced boomerangs is given by

$$p_{n+1} = \frac{BS}{M-n} \tag{6.3}$$

which is increasing in the number of previous R&D projects n. By picking out the boomerangs, the probability to get a backstop next time increases. If p increases the threshold pollution level that triggers R&D decreases. Hence, if the first innovation is a boomerang, further R&D occurs earlier and more often than in a situation with the same initial but constant p. See Figure 6.1 for such an optimal pollution and R&D program (here: $M = 7$, $BS = 3$). The innovation triggers are again indicated by the dotted lines. In contrast to Figure 5.1 where p is constant, they are decreasing in n. Interestingly, it is optimal to develop up to 3 additional boomerangs in this situation, i.e. $\hat{N} = 4$. Although after three research 'failures' a further R&D project would, according to the planner's beliefs, produce a backstop with certainty in this specific case, it is not optimal to spend R a fourth time. This somewhat surprising result is driven by the fact that even a 'failure', i.e. the development of a boomerang technology, relaxes the dynamic constraint to some extend. The benefit of decoupling and hence the incentives for further R&D are decreasing in the number of technologies in the portfolio. In the specific case presented here, the resolution of uncertainty, i.e. increase of p to $p = 1$, occurring when the fourth boomerang arrives is outweighed by the reduced benefits a backstop is able to generate. Hence, R&D optimally stops although a backstop is 'just around the corner'.

Stocks overshoot if innovation occurs at least once and M is not binding. However, in contrast to the case with a constant probability, the latter is not a necessary condition. Overshooting can occur even if M is binding. Since pollution thresholds decrease in the number of developed technologies it is possible that even with a

[1] It is assumed that the planner's beliefs are correct. Otherwise it would be necessary to specify an updating rule for the case when observations contradict beliefs, e.g. if the number of boomerangs drawn from the urn exceeds $M - BS$.

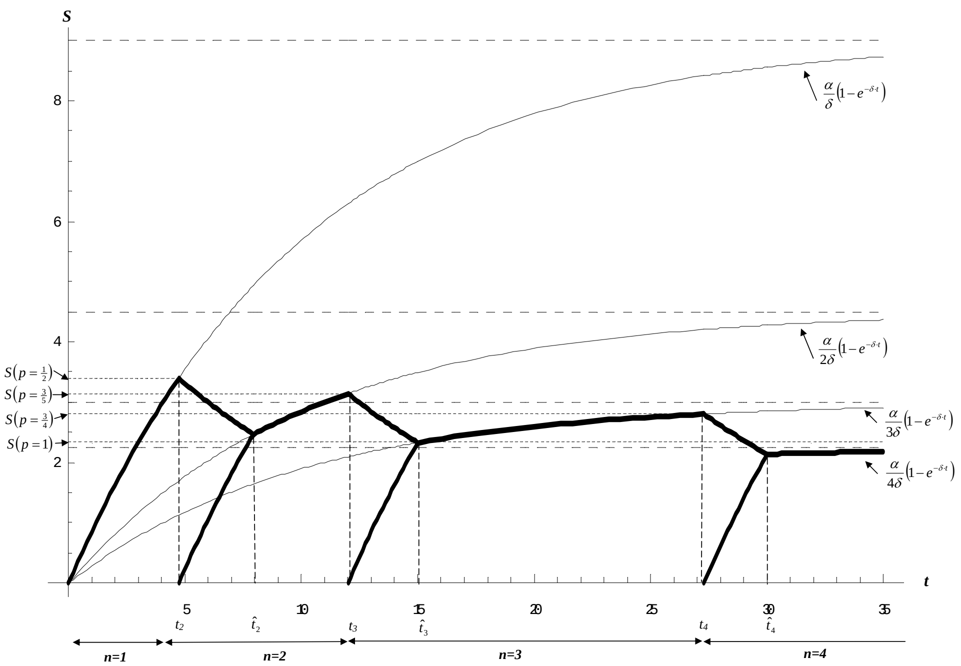

Figure 6.1: Technological Optimist: Optimal evolution of stock and R&D sequence (N=*4*) when R&D fails to develop a backstop ($M = 7$, $BS = 3$).

binding M the long-run steady state is below the initial trigger levels. Moreover, in a scenario of technological optimism, it is possible that innovation occurs before pollution stocks of existing technologies have converged. Compared with the same initial but constant p, the maximum number of technologies developed in the 'technological optimist' scenario is larger. The effect on the expected number of technologies is ambiguous, since both p and $\hat{N}$ increase.

Note that the case with a constant probability to develop a backstop is a limiting case of the technology optimist scenario. If M (and maybe also BS) becomes very large the marginal effect of an increase of n on p becomes negligible. In the limit, p is constant.

6.2.2 The Technology Pessimist

The planner believes to know M but is aware that his belief on the number of backstops, BS, is just a guess. Given some prior $\tilde{BS}$ he updates it using Bayes' rule after observing the outcome of each completed R&D project. Based on these posterior beliefs the planner then decides whether and when to engage in research again. As before, the appropriate stochastic setting is one of drawing from an urn without replacement. However, the updating process in a setting without replacement is excessively complicated if one intends to allow for sufficient flexibility with respect to the maximum number of draws, M, and the prior held by the social planner. For the limiting case where M approaches infinity, the concepts with and without replacement converge. In the case with replacement, draws provide information with respect to the number of backstops in the urn. Since only draws that produce boomerangs are relevant for the updating, the expected probability to acquire a backstop decrease in n. Without replacement, there is an additional effect, namely a reduction in the number of further technological solutions available. Given any belief $\tilde{BS}$ with $E(\tilde{BS}) > 0$ a decrease in the number of remaining solutions, ceteris paribus, increases the probability to get a backstop by the next draw. Hence, the case with replacement yields an evolution of p that represents a lower bound on the corresponding path of p in the case without replacement. In order to use a tractable specification an urn with replacement is assumed.

The prior $\tilde{p} = \frac{\tilde{BS}}{M}$ of the social planner is assumed to be a beta distribution over the interval of feasible probabilities $[0, 1]$

$$f\left(\tilde{p}|BS, M - BS\right) = \frac{1}{B(BS, M - BS)} p^{BS-1}(1-p)^{M-BS-1}. \tag{6.4}$$

Since the social planner is risk neutral, he uses the expected value of $\tilde{p}$ to make his decision. For the first R&D project (i.e. the second technology) this is given by $p_2^E = E_\beta(\tilde{p}|BS, M - BS + 1) = \frac{BS}{M+1}$. After observing the outcome of the first R&D project he updates his beliefs which again yields a beta distribution. This, however, is only of interest if a boomerang is produced. If a backstop is developed research ceases anyway and the belief about p is no longer relevant to any of the social planner's decisions. After the draw of n boomerangs (including the initially available technology) the expected probability that the $n + 1^{st}$ technology is a backstop is

$$p_{n+1}^E = E_\beta(\tilde{p}|BS, M - BS + n) = \frac{BS}{M + n}. \tag{6.5}$$

This is decreasing in n. The pollution threshold level therefore increases in the number of technologies already developed (see Figure 6.2). Similar to the baseline scenario innovation occurs only when all technologies have symmetric stocks and are hence used simultaneously. Overshooting can occur if innovation occurs at least once and M is not binding. However, in contrast to the situation with a constant p the latter is no longer a sufficient condition. Since threshold levels increase in n, the long-run steady state can be above the threshold level of the last technology developed. In this case no overshooting occurs although M is not binding. Moreover, in contrast to the case with a constant p, it is possible to end up in the incomplete steady state even after innovation has occurred and if M is not binding. Again, compared to a similar initial but constant p, the maximum number of technologies is lower. The effect on the expected number of technologies is ambiguous since both p and $\hat{N}$ decrease.

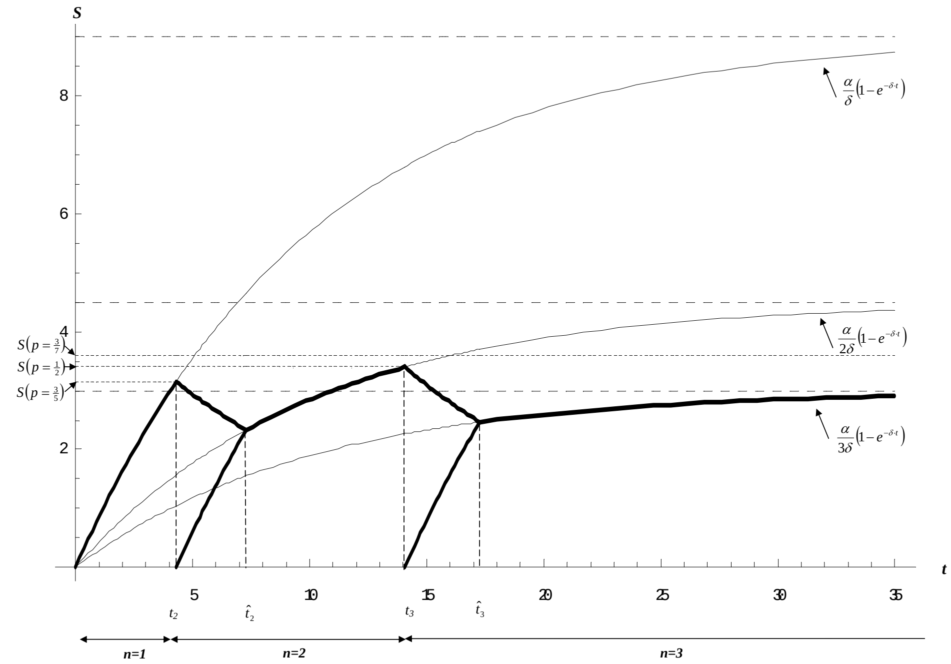

Figure 6.2: Technological Pessimist: Optimal evolution of stock and R&D sequence (N=3) when R&D fails to develop a backstop ($M = 4$, $\tilde{BS} = 3$).

The case of a constant probability to develop a backstop discussed in chapter 5 can be seen as a limiting case of both scenarios where beliefs are evolving. If the number of feasible technological solutions M approaches infinity, an additional draw has only a negligible effect on p. The probability to develop a backstop is approximately constant, both in the technology optimist and the pessimist scenario. Hence, if the pool of ideas to (partially) achieve a decoupling of goods production and damage is sufficiently large, a constant p is a reasonable approximation. With a limited pool of ideas however, how the planner evaluates information on the number of backstops in this pool is crucial. Continuing failures of R&D projects results in quite distinct evolutions of beliefs and hence research trajectories, depending on whether the planner believes to have knowledge about BS or not.

6.3 Generalized functional specifications

Here a generalization of the social welfare function from (3.6) to (3.3) is considered which allows for asymmetry between technologies. As a result, additional R&D motives that are determinants of empirically observable innovation and pollution activities will now enter into the analysis. In contrast to the previous section, both the R&D and the pollution policy are now directly affected.

A first step in the analysis is to consider the social planner's problem (3.7) now based on the general instantaneous welfare function (3.3) while retaining all linearity assumptions such that $\beta = 1$ and $c_i(q_i, t) = c_i q_i$. With the symmetry assumption regarding technologies removed, the $n+1^{st}$ technology can improve on the n^{th} technology in the form of a lower accumulation rate per unit of output, $\alpha_{n+1} < \alpha_n$, a faster rate of stock decay, $\delta_{n+1} > \delta_n$, a lower marginal damage of pollution, $d_{n+1} < d_n$, or a lower cost of production, $c_{n+1} < c_n$. The long-run properties of the pollution stocks now take into account the heterogeneity of pollutants such that the long-run equilibrium stock of pollutant i given n technologies is

$$S_i^*(n) = \frac{(\delta_i + r)(1 - c_i - \kappa_n)}{\alpha_i d_i}, \tag{6.6}$$

where

$$\kappa_n = \frac{\sum_{i=1}^n \frac{\delta_i(\delta_i+r)(1-c_i)}{\alpha_i d_i} - 1}{\sum_{i=1}^n \frac{\delta_i(\delta_i+r)}{\alpha_i d_i}},$$

is the steady-state shadow price of the output constraint given n technologies. Since the $n+1^{st}$ technology unambiguously improves on the n^{th} technology, $\kappa_{n+1} - \kappa_n > 0$ and the difference increases with the magnitude of the improvement. The long-run pollution stocks of all previous technologies therefore decrease with the number of technologies used and they decrease by more than in the case of symmetric technologies. While the long-run steady-states targeted by pollution policy therefore reflect the heterogeneity in technologies, the fundamental properties of the approach paths remain unchanged on account of the linearity of the pollution control problem. As before, the optimal pollution policy involves a sequence of at most (a) a most-rapid approach (of the singular solution), (b) a convergent singular solution path, and (c) a stationary singular solution (the steady state). With the optimal pollution policy qualitatively unchanged, a period of exclusive use of the most recent technology does still exist.

An important implication of (6.6) is that heterogeneity in all parameters other than cost c_i has no qualitative impact on the optimal pollution policy: With $c_i = c$

< 1, $\alpha_i > 0$ and $d_i > 0$ for all i, all long-run stocks will be positive, implying that all technologies will be used simultaneously in the steady state. If - on the other hand - R&D delivers improvements in the cost of production such that $c_{n+1} < c_n$ for all $n > 1$ then there exist numbers of technologies $n^1, n^2, ...$ for which the long run stock of the first, second and so on technology will be zero and the technology will be permanently discontinued in the steady-state. This implies that while the long-run steady-state will feature the use of several technologies at once, the steady state is no longer guaranteed to include *all* available technologies.

Even under the retention of the linearity assumptions, the optimal R&D policy remains inconclusive without the imposition of considerable structure on the characteristics of new technologies. On the one hand, technological improvements in subsequent technologies provide greater initial incentives for R&D. In the present set-up, these additional incentives are reflected in the optimal innovation point t^*_{n+1} determined by (5.6). Improvements in technological characteristics of the $n + 1^{st}$ technology enter into (5.6) via a lower shadow price μ^*_{n+1}, thus making it optimal *ceteris paribus* to engage in R&D earlier. On the other hand, (5.6) also implies that greater initial incentives for R&D do not necessarily translate into more cumulative R&D overall: Compared with a setting of symmetric technologies, returns from investing in the $n + 1^{st}$ technology are *ceteris paribus* lower the better the portfolio of the previously developed n technologies. This 'competitive pressure of the past' is reflected in the weighted shadow prices of previous technologies $\sum_{i=1}^{n} \mu^*_i q^*_i$ and a result of the substitutability of technologies in production. The net effect can be fully derived for specific R&D production functions only (in terms of expected properties of novel technologies) and is the subject of future research.

Other possible generalizations of the model include non-linearities in the social welfare function, e.g. the cases of $\beta < 1$ and $c(q,t) = c(q)$ with $\frac{dc}{dq} > 0$. As discussed in chapter 3, in the case of $\beta < 1$, the policy-maker faces decreasing marginal returns from production in each single technology and R&D incentives exist for reasons of product differentiation. Similarly, with increasing marginal cost of production in each technology, diversification of production allows escaping from decreasing net returns, leading to similar R&D incentives as in the case of $\beta < 1$. With the general direction clear, considering the specific impact of these generalizations on the results requires a restatement of both the optimal R&D and the optimal pollution policy. The reason is that with the linearity in the optimal pollution policy removed, the results change not only quantitatively, but also qualitatively. The result will be pollution policies that are characterized (a) by the absence of discontinuities in production shares by different technologies on account of the concavity of the net benefit function and (b) more cumulative R&D on account of the additional rents from technology differentiation (Gancia and Zilibotti 2005).

Chapter 7

Conclusion of Part I

In much of the literature on environmental R&D, it is common to assume that the outcome of the next (or most recent) R&D effort will be a backstop technology that resolves the intertemporal constraints of the environmental problem forever. This is a productive modeling shortcut that has enabled important results on the optimal timing of R&D to be derived under very general conditions. However, its premise is empirically at least arguable, as illustrated with prominent examples. In this part, a situation in which the next R&D effort generates two possible types of technology, either a backstop technology or another polluting technology (referred to as a 'boomerang'), is considered. The type of technology generated is only revealed after R&D expenditure has been incurred. The impact of this technological uncertainty on the optimal R&D and pollution policy for a policymaker faced with stock pollution and costly R&D is analyzed. A simple and tractable model is developed in which recent results on the necessary conditions of multi-stage optimal control problems are applied and extended to include technological uncertainty. This allows an intuitive and natural representation of the discrete nature of technological change. A small, but novel extension of the theory to simple discrete probability distributions over possible stages based on the policymaker's beliefs about the relative likelihood of a backstop or a 'boomerang' is presented.

Chapter 5 provides a full characterization of the optimal policy in the context of the model. Given the optimal pollution policy, the degree of technological uncertainty does not affect the fundamental structure of the optimal R&D policy, which is strictly sequential and has an endogenous stopping point. However, the timing of innovations and the maximum size of the technology portfolio are affected: To the extent that invention of a backstop becomes less likely, R&D is carried out later and the maximum number of technologies is smaller. The lower productivity of

R&D in expected terms spills over into environmental policy in the form of higher equilibrium pollution stocks.

The properties of the optimal policy depend technically on the assumptions about the welfare function, the symmetry of boomerang technologies, the capacity constraint in output, and the specific characterization of R&D. Some qualifications are therefore in order. In chapter 6 it is shown that both (a) varying costs of R&D and (b) evolving beliefs over the probability to develop a backstop change the timing and amount of research but leave pollution policies unaffected, while only the former can result in an infinite sequence of R&D; (c) asymmetries among boomerang technologies leave, with the exception of cost differentials, the qualitative nature of pollution policies intact. The effect on the amount of R&D carried out depends crucially on the expectations about the properties of future technologies. If costs differ between technologies, the optimal portfolio may exclude the more expensive types forever, even if no backstop is developed. (d) In the case of decreasing marginal returns in each technology, the pollution policy will be characterized by an absence of discontinuities in production and more R&D overall due to additional gains from product differentiation. Generalized pollution dynamics (see e.g. Tahvonen and Salo (1996)) would lead in some cases to ambiguous effects on the optimal policy choice. It is generalizations of this type that are important areas for future research.

This part focused exclusively on the social planner's problem. Hence the results state what ought to be, abstracting from what is actually feasible in a decentralized economy. The next two parts attend to the issues of implementation, considering taxes and permits to internalize pollution externalities and patents to stimulate private R&D. Chapter 14 of part II presents the implementation strategy to achieve static efficiency while chapter 21 of part III discusses the feasibility of dynamic efficiency.

Part II

Green Horizontal Innovation: Implementation[1]

[1]This part is based on Perino (2007).

Chapter 8

Introduction to Part II

Inducing technological progress that reduces damage to the environment per unit of output is at the heart of modern environmental policy. The performance of environmental regulation depends on a number of factors including its ability to internalize externalities, the type of incentives it creates to adopt existing advanced technologies (Milliman and Prince 1989, Jung et al. 1996, Requate and Unold 2003) and the degree to which it stimulates R&D.[1]

The full set of issues has so far been explored only by a small number of papers. In a two-period, competitive output market model Laffont and Tirole (1996b) study a very specific type of innovation where the new technology is perfectly clean. In this situation permits achieve static efficiency but completely expropriate the patent holding firm if the government can adjust policy after innovation has occurred. This type of analysis has been extended by Denicolò (1999), who considers a more general type of innovation where the new technology still emits pollution but has a lower emission-output ratio. Since private costs of production are assumed to be the same, the new technology is strictly superior to the established one. Without pre-commitment by the government and an exogenous quality of innovation both taxes and permits implement the static first best allocation and induce positive and identical R&D incentives.[2] Fischer et al. (2003) confirm the equivalence result. In a recent paper, Requate (2005a) studies a situation with heterogeneous firms where partial adoption is socially optimal. In a situation with flexible policies he finds that neither taxes nor permits are able to implement the static first best allocation due to monopoly pricing by the patent holding firm. Moreover, the two instruments

[1] See Requate (2005b) for a recent review.

[2] The case considered by Laffont and Tirole (1996b) is a special case where the equivalence still holds but research incentives are zero.

are no longer equivalent. This contrasts the case of pure adoption, i.e. without patents, by symmetric firms where permits always implement the optimal mix while taxes create multiple equilibria of which only one is efficient (Requate and Unold 2003). Both taxes and permits induce efficient adoption of an advanced abatement technology if firms are heterogeneous (Requate and Unold 2001).

What all previously mentioned papers have in common is that they consider a vertical innovation process: Goods and pollutants produced by new technologies are identical to those produced by old technologies, although emissions per unit of output are lower. Hence, unless the installation of the new technology involves real costs or firm heterogeneity (as in Requate and Unold (2001), Requate (2005a)) complete adoption is optimal.

In the tradition of Laffont and Tirole (1996b), Denicolò (1999) and Requate (2005a) this part studies how taxes, permits and patents perform in regulating externalities and stimulating research when innovation is horizontal. Chapters 9 to 13 concentrate on a two period, two technology version of green horizontal innovation. In this situation both taxes and permits can fail to implement the static optimum if a mix of technologies is first best. However, it is shown that by combining both instruments one can implement the static first best. The simultaneous use of emission taxes and permits is feasible, since under green horizontal innovation there are two pollutants that can be regulated using separate instruments. Moreover, some results have implications for vertical environmental innovation by qualifying previous findings. Chapter 14 then extents the framework to the continuous time and multiple technologies model introduced in part I.

The remainder of this part is organized as follows. Chapter 9 sets up the 2x2 model. The social optimum is derived in chapter 10. Chapter 11 analyzes permits, while taxes are treated in chapter 12. Chapter 13 shows how inefficiencies can be tackled by a mix of instruments. The model is extended to continuous time and multiple innovations in chapter 14. The last chapter concludes this part.

Chapter 9

The Model

As in Denicolò (1999), consider two succeeding periods in a competitive market for a non-durable consumption or intermediate good q. In the first period only one production technology, denoted by the subscript 1, is available. If the research firm successfully engages in R&D, a second technology, denoted by the subscript 2, producing a perfect substitute to q and emitting a second type of pollution becomes available in period 2.[1] The market's downward sloping inverse demand function in each period is

$$P = P(q),$$

where $q = q_1 + q_2$ is aggregate output.

Individual firms have U-shaped cost functions and are assumed to be small. Entry into the market is free. The industry's aggregate cost function is assumed to exhibit constant returns to scale, i.e. $C(q_1, q_2) = c_1 q_1 + c_2 q_2$, where c_i is the constant marginal cost of technology i at the industry level. The robustness of results to changes in the cost structure is discussed in later sections.

Each technology i emits pollution as a joint product at a constant ratio to output q_i. Technology 1 - the established one - produces only emissions of type 1. The new technology 2 emits less or no emission of type 1 and - this point is central to this paper - emissions of type 2. The social damage function D is assumed to be of the following form

$$D(q_1, q_2) = D_1(q_1 + \alpha \cdot q_2) + D_2(q_2), \quad \text{with} \quad 0 \leq \alpha < 1,$$

where both D_1 and D_2 are increasing and convex. α is an exogenous parameter

[1] The assumption of perfect substitutes is realistic if the new technology is an end-of-pipe equipment or as far as consumers do not care about the origin of the electricity they use, the type of refrigant that cools their food and the type of fuel used by their cars.

indicating by how much technology 2 is cleaner than technology 1 with respect to emission type 1. In a richer game, the research firm can be expected to have some influence - but also uncertainty - on α. In what follows, it is assumed that the type of the new technology is common knowledge and exogenous. By adding D_1 and D_2 the environmental damages of emission types are assumed to be independent, i.e. they do not increase or offset the damage done by the other pollutant. This form of the damage function allows on the one hand perfect green horizontal innovation where the new technology emits emissions of type 2 only (i.e. $\alpha = 0$) and on the other hand comes arbitrarily close to vertical environmental innovation if D_2 is very small compared to D_1.

In the first period research is undertaken by a single research firm. The probability ρ that the new technology is available in period 2 is a function of the effort R put into R&D (with $\rho(0) = 0, \rho' > 0, \rho'' < 0$ and $\lim_{R\to\infty} \rho(R) = 1$) measured by the firm's research expenditure.

In what follows, production and emission control in period 1 are ignored as there is nothing new to be learned. In the first period only the research investment matters. If the research firm's efforts remain fruitless, nothing changes compared to the first period. However, if research is successful and technology 2 becomes available in period 2 the timing is as in Laffont and Tirole (1996b) and Denicolò (1999). After the new technology has arrived and its properties are known, the benevolent government adjusts regulation and grants a patent to the research firm. Regulatory adjustment is crucial as otherwise horizontal environmental innovation allows to substitute a regulated pollutant for a non-regulated one. This would clearly create inefficiencies (Devlin and Grafton 1994). Imitation of the new technology is ruled out. Second, the research firm chooses the level of the license fee f. Third, firms decide to enter or exit the industry, which technology to use and how much to produce.

The government uses either pollutant specific tax rates or permit quantities to regulate environmental externalities. The license fee set by the research firm is assumed to be linear in output of technology 2. Since firms are small, identical and produce at an optimal scale this mimics a fixed fee per firm adopting the new technology.

Chapter 10

The Social Optimum

The social planner's solution is presented as a benchmark in this chapter. Moreover, the last section indicates how it could be implemented using forms of research stimulation other than patents.

10.1 Static Post-Innovation Efficiency

Given the new technology has arrived, the social planner aims to achieve the static optimum in period 2. He therefore maximizes the social welfare function

$$W_2\left(q_1, q_2\right) = \int_{l=0}^{q} P(l)\mathrm{d}l - c_1 q_1 - c_2 q_2 - D\left(q_1, q_2\right).$$

This yields the following first order conditions

$$P(q) \leq c_1 + \frac{\partial D_1}{\partial q_1}\left(q_1 + \alpha q_2\right), \tag{10.1}$$

$$P(q) \leq c_2 + \frac{\partial D_1}{\partial q_2}\left(q_1 + \alpha q_2\right) + \frac{\partial D_2}{\partial q_2}\left(q_2\right), \tag{10.2}$$

defining unique solutions q_1^S and q_2^S, where (10.1) is binding if technology 1 has a strictly positive output and (10.2) is binding if technology 2 has a strictly positive output.

The use of both technologies at the same time is desirable if and only if the marginal social cost of producing the first unit by technology i is smaller than the marginal social cost of producing the last unit by technology j. The analysis in subsequent chapters focuses on the interesting case where it is socially optimal to use both technologies at the same time. Some interesting features of other cases are mentioned along the way. For a detailed analysis of those, the interested reader is referred to Perino (2006).

10.2 Optimal Level of R&D

Given that the social planner is able to implement the static optimum in the second period, how much should be spent on R&D in the first period? In the first period the social planer's problem is

$$\max_R W = -R + \rho(R) \cdot \Delta W,$$

where ΔW is the welfare gain of innovation in period 2 and discounting is ignored. The corresponding first order condition is

$$\rho'(R) \cdot \Delta W = 1. \tag{10.3}$$

This defines R^S where the marginal benefit from R&D equals the marginal cost of research. Conditions (10.1), (10.2) and (10.3) fully specify the social optimum under green horizontal innovation.

10.3 Implementation Without Restrictions on Instruments

In an ideal world where there are no restrictions on instruments used and the benevolent government is able to make credible commitments, the social optimum can be implemented using pollution specific permits $\bar{E}_1$, $\bar{E}_2$ and an R&D prize.

The equilibrium of the production stage is determined by

$$\begin{aligned} P(q) &= c_1 + \gamma_1, \\ P(q) &= c_2 + \alpha\gamma_1 + \gamma_2, \\ q_1 &\leq \bar{E}_1 - \alpha q_2, \\ q_2 &\leq \bar{E}_2, \end{aligned}$$

where γ_i is the permit price for emissions of type i. In equilibrium output is given by $q_1 = \bar{E}_1 - \alpha\bar{E}_2$ and $q_2 = \bar{E}_2$ and permit prices are $\gamma_1 = P(q) - c_1$ and $\gamma_2 = (1-\alpha)P(q) + \alpha c_1 + c_2$. Hence, the government can control output of both technologies.

The optimal second period allocation can be implemented by setting

$$E_1^S = q_1^S + \alpha q_2^S, \qquad E_2^S = q_2^S.$$

In addition, a research prize of size ΔW would induce the optimal research effort.

However, the use of a research prize involves at least two restrictive conditions. First, the government has to credibly commit that it indeed pays if the new technology arrives. Second, the size of the prize has to equal the welfare gain of innovation and has to be known to the research firm in period 1. Otherwise, the level of research efforts is inefficient. Information and commitment requirements are substantial and restrictive. Hence, if the information and commitment ability of the government is constrained, research prizes fail to implement the first best optimum. Theory (Wright 1983) and their widespread use suggest that patents are usually better able to cope with these constraints. However, patents come at a cost. Granting monopoly power in the post-innovation period is likely to cause distortions and research incentives are not bound to equal the social gain of innovation. In what follows, the analysis concentrates on how patents affect static efficiency in the case of green horizontal innovation in industries regulated by taxes or permits.

Chapter 11

The Market Equilibrium with Patents and Permits

In this chapter patents stimulate research while tradeable permits are used to regulate environmental externalities. The timing is as follows. After arrival of the new technology, the government issues emission permits E_1 and E_2 to regulate pollution types 1 and 2, respectively. Second, the research firm sets a linear license fee f taking permit quantities as given. In the last stage, firms choose technologies and the market is cleared. The game is solved backwards. The qualitative results derived in this section carry over to more general cost structures like decreasing returns to scale at the industry level, e.g. due to the use of scarce inputs (Perino 2006).

11.1 Production Stage

In the free entry equilibrium of the production stage price equals average costs and permit constraints hold.

$$\begin{aligned} P(q) &= c_1 + \gamma_1 && \text{if} \quad q_1 > 0, && (11.1)\\ P(q) &= c_2 + \alpha\gamma_1 + \gamma_2 + f && \text{if} \quad q_2 > 0, && (11.2)\\ q_1 + \alpha q_2 &\leq E_1, && && (11.3)\\ q_2 &\leq E_2, && && (11.4) \end{aligned}$$

where γ_1 and γ_2 are the equilibrium permit prices for pollution type 1 and 2, respectively. The equilibrium quantities q_1^{per} and q_2^{per} are determined by (11.1)-(11.4). In what follows, it is assumed that permit quantities are set to impose at least a weak constraint on output, i.e. given a zero license fee at least one of (11.3) or (11.4) is binding. Otherwise, permits have no effect. The level of the license fee f defines three situations with respect to the number and type of technologies used: exclusive production by the established or the new technology and a mix of technologies.

Technology 1 is used exclusively ($q_2^{per} = 0$): This holds if and only if either $E_2 = 0$ or if the average cost of the new technology $c_2 + \alpha\gamma_1 + \gamma_2 + f$ is higher than the average cost of the established technology $c_1 + \gamma_1$. Since $q_2 = 0$, it follows that $\gamma_2 = 0$. γ_1 is defined by (11.1). Hence, if the license fee is sufficiently high, i.e.

$$f > \overline{f}^{per}(E_1) = (1-\alpha)P(E_1) + \alpha c_1 - c_2, \tag{11.5}$$

equilibrium quantities are $q_1^{per} = E_1$ and $q_2^{per} = 0$.

Technology 2 is used exclusively ($q_1^{per} = 0$): This holds if the average cost of the established technology is higher than the average cost of the new technology, i.e.

$$c_1 + \gamma_1 > c_2 + \alpha\gamma_1 + \gamma_2 + f. \tag{11.6}$$

How the license fee threshold for exclusive production of the new technology is defined depends on which permit constraint, if any, is binding on q_2 (see appendix).

They are summarized by

$$f < \underline{f}^{per}(E_1, E_2) = \begin{cases} c_1 - c_2 & : \quad q_2 < \min[\alpha^{-1}E_1, E_2] \\ P(E_2) - c_2 & : \quad q_2 = E_2 \\ (1-\alpha)P(\alpha^{-1}E_1) + \alpha c_1 - c_2 & : \quad q_2 = \alpha^{-1}E_1 \end{cases} \tag{11.7}$$

Furthermore, if $\alpha = 0$ the new technology produces exclusively if $E_1 = 0$ and $E_2 > 0$. Equilibrium quantities are $q_1^{per} = 0$ and $q_2^{per} = q_2(E_1, E_2, f)$.

Both technologies are used at the same time: This holds if the average costs of both technologies are the same, i.e.

$$c_1 + \gamma_1 = c_2 + \alpha\gamma_1 + \gamma_2 + f. \tag{11.8}$$

Equilibrium quantities in this case are $q_1^{per} = q_1(E_1, E_2, f)$ and $q_2^{per} = q_2(E_1, E_2, f)$. Note that this does not define a unique f but a whole set of license fees, $\underline{f}^{per} \leq f \leq \overline{f}^{per}$, since γ_1 and γ_2 are functions of f.

11.2 License Fee Stage

The patent holding firm maximizes profits $\pi = f \cdot q_2^{per}$ with respect to f given the demand $q_2^{per}(E_1, E_2, f)$ for the new technology and subject to $q_2^{per} \leq \min[\alpha^{-1}E_1, E_2]$.

The profit maximizing license fee therefore satisfies

$$-\frac{\partial q_2^{per}}{\partial f}\frac{f}{q_2^{per}} \geq 1. \tag{11.9}$$

Condition (11.9) allows for two types of equilibria. First, an interior solution where (11.9) holds as an equality. In this case permit constraints on the new technology are not binding since the research firm restricts q_2^{per} even more. Second, a corner solution where (11.9) holds as a strict inequality. Permits constrain profit maximizing of the patent holding firm. It would prefer a lower license fee and higher output of the new technology than feasible under the permit scheme.

11.3 Policy Stage

Anticipating the license fee choice of the patent holding firm and the market clearing conditions the government maximizes the following objective function with respect to E_1 and E_2

$$\begin{aligned} W_2(E_1, E_2) \quad = \quad & \int_{l=0}^{q^{per}(E_1,E_2)} P(l)\mathrm{d}l - c_1 q_1^{per}(E_1, E_2) - c_2 q_2^{per}(E_1, E_2) \\ & -D\left(q_1^{per}(E_1, E_2), q_2^{per}(E_1, E_2)\right). \end{aligned} \tag{11.10}$$

The first order conditions are

$$P(q)\left[\frac{\partial q_1}{\partial E_1} + \frac{\partial q_2}{\partial E_1}\right] = \left[c_1 + \frac{\partial D_1}{\partial q_1}\right]\frac{\partial q_1}{\partial E_1} + \left[c_2 + \alpha\frac{\partial D_1}{\partial q_2} + \frac{\partial D_2}{\partial q_2}\right]\frac{\partial q_2}{\partial E_1}, \tag{11.11}$$

$$P(q)\left[\frac{\partial q_1}{\partial E_2} + \frac{\partial q_2}{\partial E_2}\right] = \left[c_1 + \frac{\partial D_1}{\partial q_1}\right]\frac{\partial q_1}{\partial E_2} + \left[c_2 + \alpha\frac{\partial D_1}{\partial q_2} + \frac{\partial D_2}{\partial q_2}\right]\frac{\partial q_2}{\partial E_2}. \tag{11.12}$$

Note that when both permit quantities are binding in equilibrium, i.e. if $\frac{\partial q_1}{\partial E_1} > 0$, $\frac{\partial q_2}{\partial E_2} > 0$ and $\frac{\partial q_2}{\partial E_1} = 0$, conditions (11.11) and (11.12) are equivalent to the conditions for static efficiency (10.1) and (10.2).

In what follows it is assumed that static efficiency requires that both technologies are used in production. It is analyzed under which conditions the government is able to implement the first best static allocation. Since the static optimum can only be implemented if both permit quantities are binding, there is only one combination of permit quantities, $E_1^S = q_1^S + \alpha q_2^S$ and $E_2^S = q_2^S$, that is a candidate to achieve static efficiency. Both E_1^S and E_2^S are binding if and only if the patent holding firm has no incentive to deviate from the static first best allocation by setting a higher license fee. Hence, static efficiency is feasible with permits if there is a license fee

f^{per} that satisfies the following conditions evaluated in the social optimum

$$\begin{aligned} P(q^S) &= c_1 + \gamma_1, & (11.13) \\ P(q^S) &= c_2 + \alpha\gamma_1 + f^{per}, & (11.14) \\ -\frac{\partial q_2^{per}}{\partial f}\left(f^{per}\right)\frac{f^{per}}{q_2^S} &\geq 1, & (11.15) \\ \underline{f}^{per}\left(q_1^S, q_2^S\right) &< f^{per} < \overline{f}^{per}\left(q_1^S, q_2^S\right). & (11.16) \end{aligned}$$

Solving (11.13) for γ_1 and substituting into (11.14) yields $f^{per} = (1-\alpha)P(q^S) + \alpha c_1 - c_2$. (11.15) is a restriction on the price elasticity of the demand of the patent holding firm. It requires that the patent holding firm has no incentive to increase f and therefore reduce q_2 below q_2^S in order to raise profits. This is restrictive since it imposes an upper bound on the slope of the demand curve in the static optimum, in which case (11.16) is always met. The research firm will never set a license fee above $\overline{f}^{per}$ and $E_2^S = q_2^S$ implies that a reduction in f such that none of the permit constraints would be binding is impossible. Simultaneous non-binding permit constraints are only relevant if exclusive use of the new technology is first best. (11.15) is therefore a sufficient condition for feasibility of the static first best allocation. If (11.15) does not hold there are three types of inefficiency: aggregate output is too low, the relative shares of technologies are distorted and marginal social costs of technologies differ. Monopoly pricing reduces q_2^{per} below q_2^S, hence the mix is not optimal. Since the established technology is dirtier with respect to pollutant 1, the increase in q_1^{per} does not fully compensate the reduction in q_2^{per}. Aggregate output is therefore below the first best optimum. Since $q_1^{per} > q_1^S$ and $q_2^{per} < q_2^S$ marginal social costs are not equalized across technologies.

Proposition 11.1 *If a mix of technologies is statically first best, a government using permits and patents is able to implement the optimal allocation if and only if condition (11.15) holds. Otherwise, monopoly pricing by the patent holding firm distorts output in a way that the permit constraint on the new pollutant is no longer binding. Only second best allocations determined by (11.11) and (11.12) are feasible in this case.*

In contrast to the one pollutant case studied by Requate (2005a) where permits are never able to implement the optimal mix, an efficient allocation is feasible with green horizontal innovation at least in some cases. The second pollutant characteristic of green horizontal innovation generates an additional means of control available to the government. Using two instead of only one permit quantity, the government can impose different restrictions on the two technologies and thereby implement the static optimal mix at least in some cases. With respect to government's control on output, horizontal innovation is an intermediate case between vertical innovation with one pollutant and patents where permits are never optimal (Requate 2005a) and pure adoption of advanced technologies without monopoly power where permits always implement the efficient mix (see Requate and Unold (2003)).

Optimal R&D incentives are not warranted. The optimal license fee f^S is a function of pre-innovation welfare. The equilibrium license fee is not affected by this and hence in general $f^{per} \neq f^S$.

11.4 The Case of a Superior New Technology

This subsection briefly considers the case where the new technology is superior to the established one and should hence be used exclusively in the static optimum. In this case the problem effectively reduces to one with two technologies and one pollutant. A special case of this situation ($c_1 = c_2 = c$) has been analyzed by Denicolò (1999). He finds that the government can implement the static first best allocation with permits. However, his result depends on the implicit assumption that in equilibrium all permits are used by the new technology.[1] However, the patent holding firm sometimes can increase profits by raising the license fee above the threshold level $\underline{f}^{per}$ which reduces output of the new technology and triggers production by the established one (see Perino (2006)). Again, monopoly pricing results in three inefficiencies. First, aggregate output is below the social optimum. Second, the established technology produces although it should not. Third, marginal social costs of both technologies are not the same. The condition that all permits are used by the new technology and hence the static first best is implemented (if $\alpha^{-1} E_1 = q_2^S$) is

$$-\frac{\partial q_2^{per}}{\partial f}\left(f^{per}\right)\frac{f^{per}}{q_2^S} \quad \geq \quad 1, \tag{11.17}$$

which is a condition on the price elasticity of the demand function q_2^{per}. (11.17) is a necessary and sufficient condition that the government is able to implement the static social optimum. It is also necessary for the static equivalence of instruments and thereby qualifies a result by Denicolò (1999). Monopoly pricing restricts the performance of permits not only when both technologies are used at the same time (see previous subsection and the case studied by Requate (2005a)). Moreover,

[1] Fischer et al. (2003) also assume full adoption of the new technology.

both green horizontal innovation and pure emission reductions are affected by this interaction between patents and permits.

Proposition 11.2 *If the new technology is superior, condition (11.17) is necessary and sufficient to implement the static first best allocation with permits. Otherwise, monopoly pricing by the patent holding firm excessively restricts output of the new technology.*

Optimal R&D incentives are not warranted. The optimal license fee f^S that maximizes expected welfare, including the R&D stage, is given by $f^S = \frac{\Delta W}{q_2^S}$. Where ΔW is the welfare gain of innovation (see section 10.2). The equilibrium license fee depends on q_2^S and the slope of the demand curve in the optimum. Properties of the established technology that affect the social gain of innovation and hence f^S are irrelevant for f^{per}.

Chapter 12

The Market Equilibrium with Patents and Taxes

In this chapter patents stimulate research while taxes are used to regulate environmental externalities. First, the subgame perfect equilibria are derived for the case of constant returns to scale at the industry level. Section 12.4 discusses qualifications for decreasing returns to scale at the industry level.

The timing of the game is as follows. After the new technology has arrived, the government uses linear emission taxes τ_1 and τ_2 to regulate pollution types 1 and 2, respectively. Second, the research firm sets the linear license fee f taking tax levels as given. In the last stage, firms produce until price equals average costs. The game is solved backwards.

12.1 Production Stage

The free entry equilibrium of the production stage is determined by

$$P(q^{tax}) = c_1 + \tau_1, \qquad \text{if} \quad q_1^{tax} > 0, \tag{12.1}$$

$$P(q^{tax}) = c_2 + \alpha\tau_1 + \tau_2 + f, \qquad \text{if} \quad q_2^{tax} > 0, \tag{12.2}$$

where price equals average costs. The level of the license fee f again defines three situations in with only the established, only the new or both technologies produce. With constant returns to scale at the industry level it is a trivial bang-bang solution

$$q_2^{tax}(\tau_1, \tau_2 + f) = \begin{cases} 0 & : \ f > \overline{f}^{tax}(\tau_1, \tau_2) \\ \left[0, q^{tax}(\tau_1, \tau_2 + f)\right] & : \ f = \overline{f}^{tax}(\tau_1, \tau_2) \\ q^{tax}(\tau_1, \tau_2 + f) & : \ f < \overline{f}^{tax}(\tau_1, \tau_2) \end{cases}, \tag{12.3}$$

where $\overline{f}^{tax} = c_1 - c_2 + (1-\alpha)\tau_1 - \tau_2$. Note that when both technologies are used simultaneously, i.e. if $f = \overline{f}^{tax}$, individual equilibrium quantities are not uniquely defined. Only aggregate output is determined, since both technologies face the same private costs of production. Any output mix satisfying $q_1^{tax} + q_2^{tax} = q^{tax}(\tau_1, \tau_2 + f)$ is an equilibrium. Which one is actually chosen can not be determined ex-ante. With constant returns to scale at the industry level, taxes are not able to implement specific mixes of technologies (see also Requate and Unold (2003)).

12.2 License Fee Stage

The patent holding firm maximizes profits $\pi = f \cdot q_2^{tax}$ with respect to f given the demand $q_2^{tax}(\tau_1, \tau_2 + f)$ for the new technology.

If $\overline{f}^{tax} \leq 0$, output of the new technology is zero and the license fee choice irrelevant. If $\overline{f}^{tax} > 0$, the equilibrium license fee will never exceed $\overline{f}^{tax}$. Output q_2^{tax} and profit π would be zero. This can not be profit maximizing since a license fee that just undercuts $\overline{f}^{tax}$ yields both positive output and profit.

There are two candidates for the profit maximizing license fee. The first is the corner solution that just undercuts the threshold $\overline{f}^{tax}$, i.e. $f = c_1 - c_2 + (1-\alpha)\tau_1 - \tau_2 - \epsilon$, where ϵ is an arbitrarily small number. The second is a true interior solution satisfying $-\frac{\partial q_2^{tax}}{\partial f}\frac{f^{tax}}{q_2^{tax}} = 1$. Whether a true interior solution exists and thereby whether $\overline{f}^{tax}$ imposes a binding constraint, depends on τ_1 and τ_2.

Due to the research firm's license fee choice the simultaneous use of both technologies is not a subgame perfect equilibrium, regardless of the tax rates set by the government. Patents therefore eliminate the continuum of equilibria where both technologies are used (one of which is efficient) present in pure adoption games (Requate and Unold 2003).

12.3 Policy Stage

Anticipating the license fee choice of the patent holding firm and the market clearing conditions the government maximizes the following objective function

$$\begin{aligned} W_2(\tau_1, \tau_2) &= \int_{l=0}^{q^{tax}(\tau_1,\tau_2)} P(l)\mathrm{d}l - c_1 q_1^{tax}(\tau_1, \tau_2) - c_2 q_2^{tax}(\tau_1, \tau_2) \\ &\quad -D\left(q_1^{tax}(\tau_1, \tau_2), q_2^{tax}(\tau_1, \tau_2)\right). \end{aligned} \tag{12.4}$$

However, the influence of the government on equilibrium outcomes is quite limited with taxes. Regardless of the tax rates, only one technology will produce. Hence, given the focus on situations where it is socially optimal to use both technologies, the government is unable to achieve the static first best. The government's choice is limited to the choice of the technology used exclusively and to determine its output.

If the exclusive use of the established technology is second best, the equilibrium tax rates are $\tau_1 = \frac{\partial D_1}{\partial q_1}\left(q_1^{sb}\right)$ and $\tau_2 > c_1 - c_2 + (1-\alpha)\frac{\partial D_1}{\partial q_1}\left(q_1^{sb}\right)$. The former internalizes the pollution damage of production by the established technology caused at the second best level of production q_1^{sb}. The latter ensures that it is not profitable to use the new technology. Any tax rate on the new pollutant above the threshold is sufficient to achieve this.

If the exclusive use of the new technology is second best, again the tax on pollutant 1 is used to internalize the external damages of pollution, since it imposes a binding upper bound on the license fee. The second best tax rates are $\tau_1 = c_2 - c_1 + \alpha\frac{\partial D_1}{\partial q_2}\left(q_2^{sb}\right) + \frac{\partial D_2}{\partial q_2}\left(q_2^{sb}\right)$ and any τ_2 satisfying $\tau_2 < \alpha(c_1 - c_2) + (1 - \alpha)\left[\alpha\frac{\partial D_1}{\partial q_2}\left(q_2^{sb}\right) + \frac{\partial D_2}{\partial q_2}\left(q_2^{sb}\right)\right]$ and large enough to ensure that f^{tax} is indeed a corner solution just undercutting the threshold $\overline{f}^{tax}$. Note that $\tau_2 = \alpha(c_1 - c_2) + (1 - \alpha)\left[\alpha\frac{\partial D_1}{\partial q_2}\left(q_2^{sb}\right) + \frac{\partial D_2}{\partial q_2}\left(q_2^{sb}\right)\right] - \epsilon$ always satisfies both conditions. For this tax rate on the new pollutant the equilibrium license fee and profits of the research firm are zero. The choice of τ_2 from within this interval does not affect the mix or output of technologies but instead the equilibrium license fee and hence research firm's profits. Unless there is some commitment to the (newly introduced) tax on the new pollutant, the research firm faces the risk of complete expropriation when investing in R&D in the first period.

Proposition 12.1 *If a mix of technologies is statically first best and there are constant returns to scale at the industry level, a government using taxes and patents is not able to implement the optimal mix of technologies. The second best allocations are optimal given only one technology is used.*

12.4 Robustness of Results to Alternative Cost Structures

The above result is robust to some but not all variations in the cost structure. The case of constant returns to scale at the industry level requires a perfectly elastic supply of all inputs in the relevant range and that firms are small. Laffont and Tirole (1996b), Denicolò (1999) and Requate and Unold (2003) restrict their analysis to such situations. End-of-pipe equipments like scrubbers or catalytic converters are typical examples of such technologies. According to Harrison and Antweiler (2003) end-of-pipe technologies are of great practical importance in industry's abatement activities. Taxes also fail to implement specific technology mixes if all scarce inputs (that give rise to decreasing returns to scale at the industry level) are shared by both technologies. Proposition 12.1 holds in these cases (Perino 2006).

However, if some scarce inputs are specific to one of the technologies or firms are asymmetric, the result breaks down. There is no longer a threshold level where the output of the new technology is perfectly elastic with respect to the license fee. Instead of the bang-bang solution there is a region with a strictly decreasing demand for the new technology. Uniquely defined mixes of technologies therefore become feasible with taxes. This sometimes requires negative tax rates, i.e. subsidies on pollution, in order to neutralize monopoly pricing by the research firm. If such subsidies are not feasible for fiscal or political reasons, the set of parameters that allows implementation of the static optimum is considerably reduced (Perino 2006).

However, the government cannot implement the static first best in all cases even without restrictions on tax rates. The pattern is similar to the one for permits presented above. For some parameter values the static first best is feasible while for others monopoly pricing by the research firm still distorts output.

Chapter 13

Instrument Mix

The previous sections revealed that both taxes and permits fail to implement the optimal mix of technologies in some cases. The purpose of this section is to show that, if combined, their respective shortcomings cancel out. Since there are two pollutants to be regulated, it is possible to use both instruments at the same time.

Proposition 13.1 *If a mix of technologies is statically first best and there are constant returns to scale at the industry level, a government using taxes for the established pollutant, permits for the new pollutant and patents to reward research is able to implement the optimal mix of technologies.*

To prove Proposition 13.1, it is shown that $\tau_1^S = \frac{\partial D_1}{\partial q_1}\left(q_1^S + \alpha q_2^S\right)$ and $E_2^S = q_2^S$ implement the static optimum.

The equilibrium in the production stage is determined by

$$\begin{aligned} P(q^{mix}) &= c_1 + \tau_1^S, & \text{if} \quad q_1^{mix} > 0, \quad (13.1)\\ P(q^{mix}) &= c_2 + \alpha\tau_1^S + \gamma_2 + f^{mix}, & \text{if} \quad q_2^{mix} > 0, \quad (13.2)\\ q_2^{mix} &\leq E_2^S. & (13.3) \end{aligned}$$

The resulting permit price is $\gamma_2 = P(q^{mix}) - c_2 - \alpha\tau_1^S - f^{mix}$. The profit maximizing license fee is $f^{mix} = P(q^{mix}) - c_2 - \alpha\tau_1^S - \epsilon$, i.e. the equilibrium permit price is zero. The average private cost of the new technology is therefore just below that of the established technology. Hence, its output is bound by the permit constraint, i.e. $q_2^{mix} = q_2^S$. Deviations from this license fee unambiguously reduce research firm's profit: an increase in f^{mix} results in an indetermined or even zero market share (see (12.3)) while a reduction of f^{mix} leaves output of the new technology unaffected since the permit constraint is binding. The output of technology 2 is therefore optimal.

The established technology is marginally more expensive than the new one. But since the output of technology 2 is constrained by permits, there is still a demand for technology 1 of size $q_1^{mix} = q\left(c_1 + \frac{\partial D_1}{\partial q_1}\left(q_1^S + \alpha q_2^S\right)\right) - q_2^S$. However, this is exactly the first best quantity q_1^S. The first best allocation is therefore implemented by a combined use of taxes and permits.

Research incentives are given by the research firm's profit, i.e. $\pi = f^{mix} \cdot q_2^S > 0$. Although strictly positive, they are not first best, since they are unaffected by the welfare gain induced by innovation.

In the absence of commitment, i.e. when the government chooses (as is assumed here) both the instrument and stringencies at the beginning of the second period, it has a weak preference for the mixed tax-permit scheme. With constant returns to scale it weakly dominates permits and is strictly better than taxes, since the first best mix of technologies can always be implemented.

This implementation strategy does not work for general cost structures. A key requirement for the combined use to implement the static optimum is that the tax rate on the established pollutant imposes a binding upper bound on the license fee. This is necessary to correct the inefficiencies present under pure permit regulation. If there are technology specific scarce inputs, this is no longer the case. The mechanism that improves the performance of a pure tax scheme reduces that of the mixed tax-permit scheme.

Requate (1993) also uses a combination of price and quantity controls to correct for market power. In a duopolistic setting where firms emit a homogeneous pollutant he shows that permits and a subsidy on output implements the social optimum.

Chapter 14

Implementation of the Optimal Pollution Policy for Multiple Green Horizontal Innovations

So far this part focused on a simplified game with two discrete periods and at most two technologies. In such a situation a mix of instruments is able to implement the optimal post-innovation allocation. However, research incentives are not optimal in general and potential problems arising from multiple innovations have been ignored. In this chapter the insights regarding the regulation of technologies with specific pollutants are used to check if and how the social planner's pollution policy derived in part I can be realized in a decentralized economy. Hence, it generalizes the implementation strategy presented in the previous chapter to situations with multiple innovations, and hence multiple patent holding firms, and continuous time. The implementation of the optimal research policy is presented in chapter 21 since additional instruments introduced in part III are required to this end.

This chapter extends the analysis of part I to a situation where the industry faces a strictly downward sloping demand function but is not subject to a capacity constraint. This allows to study cases where market power of patent holding firms is a real issue.

14.1 The Decentralized Version of the Part I Economy

Recall the model presented in chapter 3. In what follows it will be adjusted in order to represent a decentralized economy where the social planner is replaced by a benevolent government and private production and R&D sectors. The demand for the consumption good q is perfectly elastic, with a marginal social gain of output equal to one and aggregate production is bound from above by (3.4). Both assumptions are highly stylized and made to facilitate the presentation of the social optimum in part I. The case of a downward sloping demand function without a capacity constraint on output will be discussed. It turns out that while the actual implementation strategies are somewhat different from the baseline case, the conditions for the feasibility of the first best trajectories are very much alike.

It is assumed that the initially available boomerang technology is not protected by patents and thereby its output is supplied competitively. New technologies can be developed by spending a fixed amount R on R&D. Hence, in contrast to the previous chapters of this part, the arrival of a new technology is certain once R has been spent. Research is undertaken by a single research firm that earns a patent for each technology invented.[1] A patented technology i, with $i \in \{2, ..., N\}$, once invented, can be used by production firms by paying a technology specific license fee f_i set by the patent holding firm.

The benevolent government can use emission fees, tradeable permits and combinations thereof to regulate the industry. Note that permits and taxes are assumed to be pollution specific. There is no banking or borrowing of permits. The government is credibly committed to grant a patent to any new technology developed. This assumption will be relaxed in chapter 21.

The optimal output mix derived in chapter 4 and illustrated in Figure 5.1 has a number of distinct phases. First, there is an initial phase when the unprotected technology produces at full capacity. Second, after innovation, there is a period of convergence where only the new technology is active. Third, there are intervals when all existing technologies produce simultaneously. Moreover, there are two phases not present in Figure 5.1: the incomplete steady state defined by (4.9) and exclusive production by a backstop technology. The aggregate output constraint (3.4) is not binding in the incomplete steady state. However, in the baseline model this is optimal only if innovation is not desirable in finite time. Hence, it is the relatively well explored case of regulating an industry using a single technology where research incentives can be ignored.

[1] Similar to the previous chapters in this part, the modeling of the research sector is highly stylized and ignores any inefficiencies arising from its internal structure. For discussions of such issues see Reinganum (1985), Aghion and Tirole (1994).

14.2 Optimal Pollution Policy with a Downward Sloping Demand Function

This section sketches the optimal pollution policy in a situation where the demand function has a strictly decreasing slope. This allows in later sections to study implementation in situations where market power of patent holding firms has the potential to distort output. In the case with a perfectly elastic demand function and a capacity constraint presented in part I market power will not induce inefficiencies and hence is less realistic.

The model is adjusted as follows. Let

$$P(Q), \tag{14.1}$$

be the inverse demand function with $\frac{\partial P}{\partial Q} < 0$ where $Q = \sum_1^n q_i$ is aggregate output. Hence condition (4.1) in chapter 4 becomes

$$e^{-rt} P(Q(t)) + \alpha \mu_i^{Boom_n}(t) = 0, \tag{14.2}$$

while condition (4.2) remains unaffected. Note that there is no capacity constraint and hence no κ. Hence, there will be no distinction between an 'incomplete steady state', a 'complete steady state' and an 'approach path'. In contrast to the baseline model, condition (14.2) is a function of aggregate output Q. In general, aggregate output is therefore restricted due to the associated damages. Optimal output is a function of the shadow price of pollution and hence of the pollution stock. Again, at each point in time all technologies with strictly positive output have identical pollution stocks and by symmetry also the same individual output. Note that in case a backstop is developed the optimal policy is as before, i.e. only the backstop produces with $q_n^{Back} = P^{-1}(0)$.

Explicitly solving for the optimal pollution and R&D policy is not straightforward. However, the different possible phases can be classified along the same categories as in the case with a perfectly elastic demand function: exclusive use of the unprotected technology, exclusive use of the most recent technology and simultaneous use of all (or any subset of) technologies. Fortunately, these qualitative results are sufficient to discuss the feasibility of implementation.

14.3 Exclusive Use of the Unrestricted Technology

This case contains two of the phases distinguished above: the initial phase characterized by production by the initially available technology at the capacity constraint and, in the baseline model, the incomplete steady state. With a perfectly elastic demand function *cum* capacity constraint the former is trivial in that it does not require any intervention by the government. The unregulated market equilibrium matches the social optimum. Although production at full capacity involves pollution and hence externalities, marginal damages are strictly smaller than the marginal benefit of production within the interval $[0, \tilde{t}]$. Here $\tilde{t}$ is either the point in time where the first innovation optimally occurs, i.e. t_2^*, or when marginal damages of production start to outweigh marginal gains and hence the incomplete steady state is reached. The incomplete steady state can be implemented by issuing a number of permits corresponding to the optimal amount of output.

For the case with a downward sloping demand function, both a tax of $t_1 = P\left(Q^*(t)\right)$ or permit quantity $E_1 = \alpha_1 Q^*(t)$ on the first pollutant solve the problem.

14.4 Exclusive Use of the New Technology

The new technology n is always protected by a patent and hence subject to monopoly pricing of the patent holding firm. However, due to the somewhat peculiar, perfectly elastic demand function, this does not result in socially undesirable reductions in output. Nevertheless, the optimal allocation can also be implemented, using strategies developed in the previous chapter, where the industry faces a downward sloping demand function.

The exclusive use of the new technology can be achieved as follows: do not regulate the new technology, impose zero permit quantities for all other technologies, except the unprotected one which faces an emission tax $\tau_1 \geq 0$. The actual level of τ_1 does not matter for static efficiency in the special case with a perfectly elastic demand function. However, with a downward sloping demand it should be set equal to $\tau_1 = P\left(Q^*(t)\right)$ and combined with a permit constraint on the new pollutant $E_n = \alpha_n Q^*(t)$ if technology n is a boomerang and $\tau_1 = 0$ if it is a backstop. This imposes an upper bound on the license fee (see chapter 13) and thereby avoids inefficiencies arising from monopoly pricing by the patent holding firm.

The patent holding firm will set a license fee f_n that just undercuts the emission tax or the reservation price of consumers and hence results in production at the capacity constraint. No other technology will produce since it is either effectively forbidden or not profitable due to a tax that exceeds the license fee. This policy is optimal during convergence, i.e. in the interval $[t_n, \hat{t_n}]$, and from t_n to infinity if n constitutes a backstop technology.

14.5 Simultaneous Use of All Technologies

After convergence and before any subsequent innovation the simultaneous use of all available boomerang technologies is optimal. Again, implementation using a combination of taxes and permits is straightforward. Issue permit quantities $E_i = \alpha_i q_i^{Boom_n^*}$ for all $i = 2, ..., n$ and set a tax rate $\tau_1 \geq 0$. Again, with a downward sloping demand function the tax rate is uniquely defined as $\tau_1(t) = P\left(Q^*(t)\right)$, while it does not matter for static efficiency in the context of a perfectly elastic demand function.

For the case with a downward sloping demand function, using only taxes and permits as instruments, research incentives are completely determined after implementing the optimal pollution policy. Hence, in general they are not optimal. For the case with a perfectly elastic demand function the tax rate on the unprotected technology is usually not uniquely defined and therefore can be used to adjust research incentives without jeopardizing static efficiency. However, it affects all technologies and hence all patent holders at the same time. Feasibility of the optimal R&D program, hence, is unlikely. Part III introduces additional instruments that are observed in real world regulatory schemes and that give additional control to the government. These more flexible instruments are first discussed in two period, two technology settings before the optimal R&D policy for the case of multiple innovations is discussed in chapter 21. Without such additional instruments only second best policies can be implemented. This chapter showed that static efficiency is feasible. In the absence of commitment by the government this is also the unique closed loop equilibrium, given the set of instruments.

Chapter 15

Conclusion of Part II

Green horizontal innovation, where new technologies reduce pollution of one type while causing a new type of damage, is highly relevant but not sufficiently considered in the economics literature so far. This part considers such a situation to study the performance of taxes and permits in regulating externalities in the presence of patents. The focus is on situations where the simultaneous use of multiple technologies is optimal. Cases with a superior technology are equivalent to the single pollutant case and are already covered in the literature.

In a simplified model with two periods and two technologies permits can implement the static optimum at least in some cases where both technologies are used at the same time. This contrasts their performance under vertical environmental innovation (i.e. where only one pollutant is emitted), in which case the optimum mix is never feasible with the use of patents (see Requate (2005a)).

The reason that permits fail to implement the optimum in some situations is their very nature of imposing upper bounds on quantities. Although environmental externalities in general ensure that the first best output is below the unregulated output, this does not necessarily hold here. There is an additional market failure in the form of market power created by patents. Hence, under certain conditions the patent holding firm restricts output below the social optimum by monopoly pricing. This creates up to three types of inefficiency: reduced aggregate output, suboptimal mix of technologies and violation of the equimarginal principle.

With constant returns to scale at the industry level, taxes suffer from the inability to implement specific technology mixes, which is well known from the literature on vertical innovation (Requate and Unold 2003). For other cost structures, however, the optimal mix can in some cases be implemented using taxes. This contrasts the case of vertical innovation, where under both taxes and permits monopoly pricing by the research firm always distorts outcomes (Requate 2005a).

Although both instruments fail to implement the static optimum in general, their weaknesses cancel each other out if both are used at the same time. The basic feature of green horizontal innovation is that there are different pollutants causing different types of damages. Hence, it is possible to regulate the established pollutant via a tax and the new one by permits. This mixed tax-permit scheme is shown to achieve an efficient technology mix when there are constant returns to scale at the industry level. This is exactly the situation where the failure of a pure tax scheme is most severe. Existing tax schemes should hence be supplemented by permits rather than another tax when an alternative technology emitting a new pollutant emerges.

In addition to the new insights created for green horizontal innovation, some previous results on vertical innovation are qualified. It is shown that monopoly pricing is also an issue in situations with only one pollutant and a strictly superior technology if permits are used. It is a general pattern that granting patents to induce private innovation incentives triggers monopoly pricing by the successful research firm. This in turn restricts the performance of economic instruments to regulate environmental externalities in the post-innovation period. In itself, this is not a surprising result. However, previous studies in this area have somewhat obscured this fact by basically assuming it away. Both, the evaluation of its empirical relevance and its effect on the desirability of patents compared to other instruments, await further research.

In chapter 14 the insights derived in previous chapters of this part are applied to an economy underlying the analysis in part I. It is possible to specify a sophisticated policy using hybrid tax-permit schemes that is able to implement the socially optimal pollution trajectories for a decentralized version of such an economy. This implementation strategy is robust to generalizations such as an economy with a downward sloping demand function.

More flexible instrument designs that allow for additional control over post-innovation allocation and research incentives are studied in the next part.

Part III

Endogenous Design of Environmental Regulation, Commitment and Intellectual Property Rights

Chapter 16

Introduction to Part III

Environmental policy often faces commitment problems when firms invest in abatement technologies. Once investments are sunk, even a social planner might want to deviate from the policy previously announced to induce investments in order to improve static efficiency. Solving this problem of time-inconsistency requires credible commitment by the government. Overcoming the commitment problem through contracts is not trivial in a setting involving firms and government since there is no third party with the necessary power to enforce them (Acemoglu 2003).[1] Although an independent judicacy can force a government to stick to its own rules, the government can change the very rules at will. If commitment devices are thus limited, there are two key determinants of the time-inconsistency problem. First, the choice set of the government and second, its objective function. This part considers both dimensions. The link between the organization of government and its ability to commit are studied in part IV.

Different reasons for time-inconsistency to arise have been discussed in the literature. In Gersbach and Glazer (1999), future environmental policies announced to induce firms to invest involve excessive social costs in the absence of investment. The government therefore has no credible threat point. They show that grandfathered permits, i.e. a commitment to a specific instrument, can solve the hold-up problem. Policies in Marsiliani and Renström (2000) are time-inconsistent because investment is irreversible. Hence, after firms have invested the government has incentives to reduce the emission tax in order to implement the ex-post static optimum. They study earmarking of tax revenues as a commitment device given earmarking is credible.

[1] In a recent paper Acemoglu and Johnson (2005) find that restrictions on predatory practices of governments has been more important to the prosperity of nations than the enforcement of private contracts.

Thereby they introduce a complimentary instrument where commitment is assumed to be feasible. A somewhat different source of time-inconsistency, focusing on government's objective function, is presented by Abrego and Perroni (2002). They study the case where environmental regulation affects the distribution of income while the government has an distributional objective. Abrego and Perroni (2002) show that investment subsidies can substitute for policy commitment.

These approaches have in common that investments are firm specific and represent adoption of abatement technology. However, in the medium and long run original R&D is the prime source of new abatement technologies and private incentives to undertake research are therefore essential. A firm that invests into R&D produces new knowledge, i.e. a public good. Unless the government ex-post grants and protects intellectual property rights, e.g. in the form of patents, the research firm can appropriate only a small fraction of the social benefits of its investment. However, patents come at a cost to society. They create static inefficiencies due to monopoly pricing (see part II). Hence, even a benevolent government faces a commitment problem because ex-post it would increase static efficiency if the new technology is used by all firms at its marginal cost.

Laffont and Tirole (1996b) study this problem in a setting where pollution is regulated by permits and R&D yields a perfectly clean technology. They show that, even if intellectual property rights are perfectly enforced, without commitment on environmental policy there will be no R&D because ex-post the government sets a permit quantity that drives the license fee down to zero. The research firm is effectively expropriated and anticipating this the R&D sector does not invest in the first place. However, Denicolò (1999) shows that this is only a special case. If the new technology does still emit some pollution, research incentives are positive, though not first best. This holds both for taxes and permits. This result has recently been confirmed by Requate (2005a) who studies a type of innovation where partial adoption of the new technology is optimal.

Building on Laffont and Tirole (1996b) and Denicolò (1999) the contributions of this part are threefold. First, the choice set of the government is extended. It is no longer confined to only one parameter per instrument (e.g. a tax rate or a permit quantity). Instead, the environmental instrument and its design are endogenous. This increase in flexibility is achieved by allowing that permits have an upper and lower bound on prices (Roberts and Spence 1976, Pizer 2002). Both taxes and plain permits are special cases of this more general scheme. Second, the objective function of the government is extended. In addition to welfare maximization in a first best setting, the paper analyzes how a revenue objective of the government does affect static and dynamic performance. Intuitively, putting additional weight on government's revenues should increase its predation propensity. In some cases this intuition is confirmed. However, in other situations a revenue objective turns out to be a research stimulating commitment device. Third, the class of innovation types is extended. Four types, including vertical innovation (Laffont and Tirole 1996b, Denicolò 1999), a clean but expensive substitute (Abrego and Perroni 2002) and multiple green horizontal innovations are analyzed. In contrast to previous parts situations involving only one type of pollution are studied.

In the real world, the choice set of the government is considerably larger than assumed by previous studies. Contrary to the standard assumptions, neither the instrument of regulation nor its design are fixed. For example, the rules of the sulphur trading program in the U.S. state explicitly that permits do not constitute property rights and might be removed without compensation. But even if permits continue to be used, whether they are grandfathered or auctioned, the design of auctions and complementary instruments are subject to change. Such changes in design can effectively alter the nature of an instrument, e.g. if they impose explicit or implicit bounds on permit prices.

Reservation prices are used in auctions of oil and gas leases (Opaluch and Grigalunas 1984, Hendricks et al. 1994). An additional tax on emissions (or related inputs) and an abatement subsidy have the same effect. Emission taxes have been used in the U.S. permit scheme for ozone-depleting substances (ODS) and in some European countries (e.g. Germany) carbon taxes supplement the European Union Greenhouse Gas Emission Trading Scheme (EU ETS).

Upper price bounds can be implemented by fixed penalties for excessive emissions not covered by permits. This was done in the former Denmark carbon and U.S. ODS permit programs (OECD 2003). In the UK renewables obligation program firms are allowed to buy themselves out at a pre-specified price. This option has been used extensively (DTI 2004).[2] A similar approach is currently discussed in Switzerland. There firms will be able to choose to be subject to a carbon tax or to participate in the EU emission trading scheme.

[2]Another common variant is a fixed penalty combined with the requirement to provide the missing permits in the following year. This is implemented e.g. in the U.S. acid rain and European carbon trading schemes. Effectively, this allows for borrowing of permits at a surcharge specified by the penalty.

The objective function of a government often deviates from pure welfare maximization in a first best world. For example, it might put some weight on its budget. The impact of such a revenue objective, caused by e.g. distortionary taxation elsewhere in the economy[3], is studied. Revenue objectives do play a role in real world environmental policy. The tax on CFC production in the ODC program has been introduced to capture windfall rents after the establishment of the permit scheme and have subsequently been raised almost fourfold (OECD 2003). The desire to raise funds for the German pension system was an important motivation to set up a carbon tax at the end of the 1990s and revenue objectives are the reason for reservation prices in U.S. oil and gas lease auctions. This paper complements the literature on environmental regulation with previous tax distortions (Bovenberg and de Mooij 1994, Babiker et al. 2003, Fullerton and Wolverton 2005) by explicitly considering research investment effects. Laffont and Tirole (1996a,b) model revenue objectives in related frameworks, but while Laffont and Tirole (1996a) concentrates on adoption decisions without patents, the results in Laffont and Tirole (1996b) do not hinge on the revenue objective.

It is assumed that environmental regulation is the only way by which the government is able to raise additional revenues. Patent rights are perfectly enforced and discretionary profit taxes are ruled out. Credible commitment is lacking only with respect to the design of environmental regulation in order to focus on this issue. This is consistent with previous approaches to model the dynamic performance of environmental regulation.[4] It is reasonable because, in contrast to patent law, environmental regulation has to be more flexible in order to adjust to new insights about damages and to new technologies (see part IV). Moreover, the assumption of credible patent law is not necessary to establish most of the results. Except for one case, with endogenous environmental regulation the government turns out to be at least indifferent to patents at the point in time it has to grant them. In what follows, time-inconsistency is therefore less of an issue for patent law.

The key results of this part are that the additional flexibility of the government in designing environmental policy makes implementation of the static post-innovation optimum feasible in a number of cases. However, flexibility often decreases research incentives while it is necessary for dynamic efficiency in the case of multiple green horizontal innovations. The effect of a revenue objective on R&D efforts is ambigu-

[3]For other reasons see Grossman (1991), McGuire and Olson (1996).

[4]See Laffont and Tirole (1996a,b), Denicolò (1999) and Requate (2005a).

ous. Depending on the type of innovation it can increase or destroy these efforts.

The remainder of this part is organized as follows. The next chapter presents the model. Chapter 18 analyzes the effects of flexible instrument design and a revenue objective in the standard case of vertical environmental innovation. In chapter 19 the case of a polluting industry facing a clean but expensive substitute is considered. Chapter 20 studies a clean industry that faces entry of new polluting technology. The implementation of the optimal R&D trajectory for the case of multiple green horizontal innovations is analyzed in chapter 21. The last chapter concludes.

Chapter 17

The Model

Like Laffont and Tirole (1996b) and Denicolò (1999) consider two succeeding periods in a competitive market for a non-durable consumption or intermediate good q. In the first period only one production technology labeled 1 is available. If the research sector successfully engages in R&D in the first period, a new technology 2 producing a perfect substitute to q becomes available in the second period. The market's downward sloping inverse demand function in each period is

$$P = P(q),$$

where $q = q_1 + q_2$ is the sum of technologies output.

Individual firms are small, have U-shaped cost functions and entry is free. Both technologies are assumed to exhibit constant returns to scale at the industry level. The industry's cost function is therefore given by

$$C(q_1, q_2) = c_1 q_1 + c_2 q_2.$$

This cost structure is more general than that of Laffont and Tirole (1996b) and Denicolò (1999) by allowing for real economic costs associated with the installation of the new technology (i.e. $c_2 > c_1$). So far the model is similar to the one presented in chapter 9. However, the damage function introduced next is different. It is assumed that at most one type of pollution is emitted and each technology is allowed to be perfectly clean.

Technologies might emit pollution as a joint product at a constant ratio to output q_i. The social damage function D is assumed to be

$$D(q_1, q_2) = D(a_1 q_1 + a_2 q_2),$$

where D is increasing and convex and $a_i \geq 0$ for all $i \in \{1, 2\}$ and $a_1 + a_2 > 0$. The latter condition ensures that at least one of the technologies is polluting and the problem therefore relevant for environmental regulation. a_i are exogenous parameters indicating by how much technology 2 is cleaner than technology 1 or vice versa. This specification of the cost and damage functions allow for a number of innovation types. Vertical innovation where the new technology is cleaner, equally costly and hence strictly preferred ($c_1 = c_2, a_1 > a_2$) analyzed by Denicolò (1999) and perfect vertical innovation ($c_1 = c_2, a_2 = 0$) considered by Laffont and Tirole (1996b) are special cases of the more general types discussed in this part.[1]

The research sector invests into R&D according to the expected value of future patents. In case of development of a new technology, the successful research firm is granted a patent in the second period. It is assumed to set a license fee f linear in output of the new technology.[2] Imitation of the new technology is ruled out, hence patents are strong and of sufficient breadth.

The government is allowed to have a revenue objective. The objective function of the government is therefore

$$G = W + \lambda B, \tag{17.1}$$

where W is social welfare in the absence of distortions elsewhere in the economy, B is the amount of public revenue raised by environmental regulation and $\lambda \geq 0$ is the weight of the revenue objective. λ might be positive because raising public funds requires distortionary taxation elsewhere in the economy. Thus, the marginal cost of public funds is allowed to be above unity.[3]

In the absence of a commitment on either taxes or plain permits, the government uses the following instrument to regulate pollution. Permit quantity E is auctioned at a reservation price $\underline{\tau}$ or if $\underline{\tau}$ is negative, given away together with a subsidy on pollution. If the permit price exceeds an upper bound $\overline{\tau}$, the quantity constraint ceases to be binding and additional permits are sold at this price. This design enables the government to choose endogenously between price and quantity regulation by adjusting stringencies within a given legal framework. The distinction made in the literature between a commitment on instruments and on stringencies becomes obsolete. The situation where the government has full flexibility on all policy variables in the post-innovation period is compared to a commitment on taxes and plain

[1] Not all types of innovation consistent with the above specification are considered. Instead the focus is on exemplary cases that nevertheless extend considerably the set studied by Laffont and Tirole (1996b), Denicolò (1999).

[2] This is equivalent to a fixed fee per firm as firms are small and face U-shaped cost functions.

[3] In what follows, it is ignored that the introduction of environmental regulation might affect the size of λ (Bovenberg and de Mooij 1994).

permits that has frequently been assumed in the literature.

In what follows, production and emission control in period 1 are ignored as there is nothing new to be learned. In the first period only the research investment matters. If the research sector's effort remains fruitless, nothing changes compared to the first period. However, if research is successful and technology 2 becomes available in period 2 the timing is like in Denicolò (1999) and Laffont and Tirole (1996b). After the new technology has arrived and its properties are known, the government adjusts regulation and grants a patent to the successful research firm. Second, the research firm chooses the level of the license fee f. Third, firms decide to enter or exit the industry, which technology to use and how much to produce.

Chapter 18

Vertical Environmental Innovation

Assume that the new technology is equivalent to the established one but emits less of the same pollutant ($0 < a_2 < a_1, c_1 = c_2 = c$, see Figure 18.1). The new technology is strictly preferred and innovation is therefore vertical. Without loss of generality assume that $a_1 = 1$. This case has been studied by Denicolò (1999) both with and without commitment on future tax rates and permit quantities. Laffont and Tirole (1996b) analyze a limiting case where the new technology is perfectly clean ($a_2 = 0$).

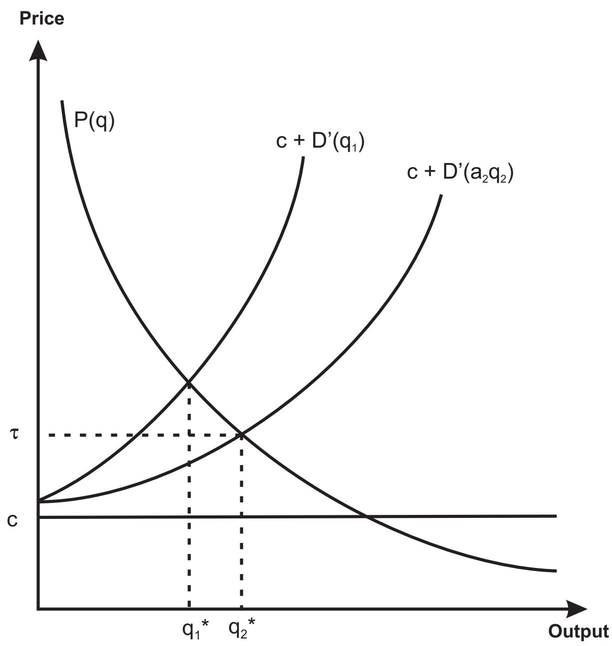

Figure 18.1: Vertical environmental innovation

18.1 No Revenue Objective

Assume that the government has no revenue objective ($\lambda = 0$). First, consider the case of plain permits without upper or lower bounds on the permit price. As will be seen, they are not always able to implement the static first best allocation. Second, it is shown that the inefficiencies can be removed by an upper bound on permit price.

In the plain permit scheme the equilibrium conditions in the market clearing stage are given by

$$P(q) = c + \gamma, \tag{18.1}$$

$$P(q) = c + a_2\gamma + f, \tag{18.2}$$

$$q_1 + a_2 q_2 \leq E, \tag{18.3}$$

where γ is the equilibrium permit price. Firms are indifferent between using the established and the new technology if $f = (1 - a_2)\gamma$. A profit maximizing patent holding firm will ensure that the license fee always satisfies this condition. If $f < (1 - a_2)\gamma$, it could raise the fee without affecting output of the new technology due to the permit constraint or, if $f > (1 - a_2)\gamma$, the new technology is not used at all. Note that this does not yet define the equilibrium license fee. The permit price depends on aggregate output which is itself a function of f implicitly defined by (18.1)-(18.3). The patent holder can influence both aggregate output and that of the new technology (Requate 2005a). Hence, the patent holding firm has some discretion on f while maximizing its profits $\pi = f \cdot q_2(f)$ subject to the permit constraint (18.3) that is always binding. The first order conditions yield $q_2 = \frac{E}{a_2}$ and $q_2 + f\frac{\partial q_2}{\partial f} = 0$ for $q_2 < \frac{E}{a_2}$. Substituting in f, (18.1), q and $\frac{\partial q_2}{\partial f} = \left[(1 - a_2)^2 \frac{\partial P}{\partial q}\right]^{-1}$ yields $q_2 + \frac{P(E+(1-a_2)q_2)-c}{(1-a_2)\frac{\partial P}{\partial q}|_{q=E+(1-a_2)q_2}}$ for the left hand side of the latter equation.

The government aims to implement $q_2 = \frac{E}{a_2} = q_2^*$ and $q_1 = q_1^* = 0$, where an asterisk denotes static first best levels. However, it follows from the profit maximizing behavior of the patent holding firm that this is only possible if

$$-(1 - a_2)^2 \left.\frac{\partial P}{\partial q}\right|_{q=q_2^*} \frac{q_2^*}{P(q_2^*) - c} \leq 1. \tag{18.4}$$

Otherwise, the patent holder increases the license fee above $f = (1 - a_2)\left[P(q_2^*) - c\right]$ and thereby reduces output of the new technology below the optimal level and triggers production by the established one. This qualifies a result by Denicolò (1999) who finds that permits are efficient given the new technology is superior by assuming that $q = \frac{E}{a_2}$ (see also section 11.4).

An upper bound $\overline{\tau}$ on the equilibrium permit price can avoid this source of static inefficiency. If $\gamma^e = \min[\gamma, \overline{\tau}]$ is the effective permit price and $\overline{\tau} = P(q_2^*) - c$, this imposes an upper bound of $(1 - a_2)[P(q_2^*) - c]$ on the license fee. For license fees exceeding this threshold, the permit constraint ceases to be binding and the entire output is produced by the established technology. This can not be in the interest of the patent holding firm. Hence, with $\overline{\tau} = P(q_2^*) - c$ any $E \leq a_2 q_2^*$ implements the first best static optimum. This includes $E = 0$, i.e. a standard emission tax.

Note, in all cases where the advanced design increases static efficiency patent holder's profits and hence research incentives are strictly lower under the flexible design than under plain permits. The bound on permit price restricts profit maximizing of the research firm.

Plain permits fail to implement the static first best in general, while taxes are equivalent to the flexible scheme. The government is therefore indifferent between a tax and the flexible instrument.

Proposition 18.1 *If innovation is vertical and the government has no revenue objective, the first best static allocation is feasible with permits if bounds on permit prices are available (but not otherwise). Research incentives are less under the flexible scheme whenever flexibility is of value. The flexible design is equivalent to a pollution tax both in static and dynamic terms.*

Research incentives are positive because the externality requires a reduction in output of the new technology compared to a situation without market failures. Thereby firms have a positive willingness to pay for the new technology given the static optimal regulation.[1] The patent holding firm can appropriate this amount by license fees. However, unless plain permits are used, there is no monopoly pricing in a sense that distorts the allocation. Hence, there is no time-inconsistency with respect to patent law. Granting intellectual property rights is a credible promise. However, the dynamic incentives created are solely determined by the size of the externality of the new technology and therefore only by chance first best.

18.2 With Revenue Objective

In case λ is strictly positive the government faces a trade-off between static efficiency and revenue maximization (see equation (17.1)). It can control output using either

[1]This does not hold if the new technology is perfectly clean, i.e. $a_2 = 0$ (Laffont and Tirole 1996b).

the flexible instrument or a tax. For the ease of presentation the case of a tax τ is used in the remainder of this section.

The amount of public revenue raised by environmental regulation is given by $B = a_2\tau \cdot q_2$. Profits of the research firm are $\pi = f \cdot q_2 = (1 - a_2)\tau \cdot q_2 > 0$. Hence, the government's objective function can be rewritten as

$$G = W + \lambda \frac{a_2\pi}{1 - a_2}.$$

Public revenue is linear and increasing in patent holder's profit. Somewhat surprisingly, a revenue objective of the government increases research incentives. In this partial equilibrium model the welfare effect of an increase in λ depends amongst others on whether one starts in a situation with over or under provision of research. However, if the reason for the revenue objective is distortionary taxation elsewhere in the economy, an increase in λ would of course require to escalate these distortions.

Proposition 18.2 *If innovation is vertical and the government has a revenue objective, research incentives are positive and increasing in the weight of the revenue objective.*

The reason for the revenue objective of the government and research incentives to be in line with each other is due to the characteristics of vertical environmental innovation and, moreover, purely static. Hence, it is not based on the dynamic argument that a government with a revenue objective has a self interest in restricting future expropriation in order to increase productivity and thereby the tax base.[2] This would require commitment which is ruled out here.

Note that patent law faces time-inconsistency in this case. If innovation has occurred, the government can increase revenues by not granting a patent. With patents public revenues are $B = a_2\tau \cdot q_2^* = [P(q_2^*) - c - f] \cdot q_2^*$ while without patents they would be $\hat{B} = a_2\hat{\tau} \cdot q_2^* = [P(q_2^*) - c] \cdot q_2^*$. This is the only situation where credible commitment to patent law is crucial in this part.

[2]The latter argument has been put forward e.g. by McGuire and Olson (1996).

Chapter 19

A Polluting Industry Facing a Clean Substitute

In this chapter a different type of innovation is considered. Contrary to the type in the previous chapter, the new technology has higher marginal costs than the established one ($c_1 < c_2$) but is perfectly clean ($a_2 = 0$). Assume that the new technology is socially desirable but not strictly superior to the established one (see Figure 19.1). This case has been studied by Abrego and Perroni (2002) but for adoption decisions instead of R&D. Again, the model by Laffont and Tirole (1996b) is a limiting case where the private costs of production of the new technology become arbitrarily close to that of the established technology ($c_1 + \epsilon = c_2$). Electricity production is a case in point where wind and solar power are clean but so far more expensive alternatives to nuclear power and fossil fuels. Similarly, fuel cells provide a clean substitute to traditional combustion engines but currently at higher private costs.

19.1 No Revenue Objective

Assume that the government has no revenue objective. The equilibrium of the production stage with the flexible scheme is given by

$$\begin{aligned} P(q) &= c_1 + \gamma, \\ P(q) &= c_2 + f, \\ q_1 &\leq E, \qquad \text{if } \gamma < \overline{\tau}, \end{aligned}$$

where γ is the equilibrium permit price. The above system of equations determines the equilibrium output quantities q_1 and q_2 and the equilibrium permit price $\gamma =$

$\min[c_2 - c_1 + f, \overline{\tau}]$. Note that only an upper bound on the permit price is considered here.[1] Allowing for a reservation price would not change the results.

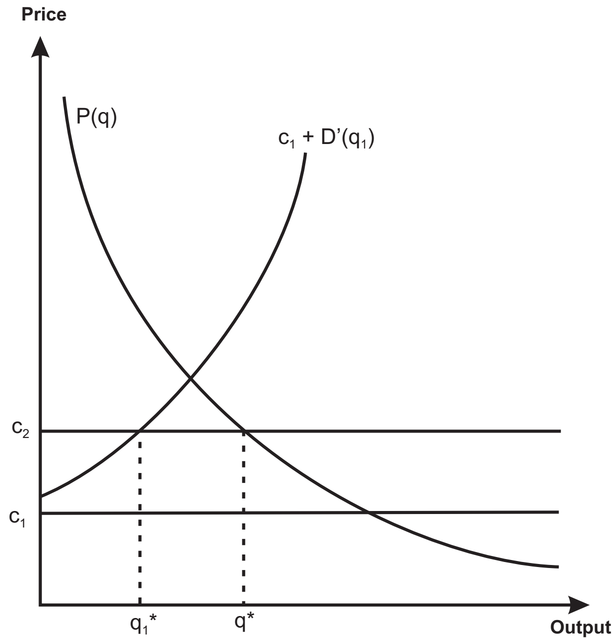

Figure 19.1: A clean but expensive substitute

In the previous stage the patent holding firm faces a residual demand

$$\tilde{q}_2(f) = \begin{cases} 0 & : \ f > c_1 - c_2 + \overline{\tau} \\ q(c_2 + f) - E & : \ 0 \leq f < c_1 - c_2 + \overline{\tau} \end{cases}$$

The research firm maximizes profits $\pi = f \cdot \tilde{q}_2(f)$ over f given the residual demand function. The equilibrium license fee is therefore $f = \min[\hat{f}, c_1 - c_2 + \overline{\tau} - \epsilon]$, where $\hat{f}$ is defined by the standard monopoly pricing condition $-\frac{\partial q}{\partial P}\frac{\hat{f}}{\tilde{q}_2(\hat{f})} = 1$ and ϵ is arbitrarily small. The maximum permit price $\overline{\tau}$ thereby imposes an upper bound on the license fee.

The government sets the policy variables E and $\overline{\tau}$ to maximize post-innovation static welfare. Due to the assumption that the new technology is socially desirable the maximum permit price has to ensure that the new technology is used in equilibrium, i.e. $\overline{\tau} > c_2 - c_1$. Any increase of $\overline{\tau}$ above this threshold results in a rise of f and therefore in a price increase and a reduction of aggregate output. In the absence of any revenue objective on the side of the government ($\lambda = 0$), the static social optimum is implemented by setting $\overline{\tau} = c_2 - c_1 + \epsilon$ and E such that $D(E) = c_2 - c_1$. Hence, $f = 0$. Market power and research incentives, purposely

[1]This is the regulatory instrument used in Pizer (2002) and effectively embodied in most permit schemes by the imposition of penalties for excess emissions.

generated by patent law, are destroyed by an opportunistic use of environmental regulation. Hence, commitment on patent law is irrelevant if environmental regulation can be freely adjusted in the post-innovation period. At the point in time the government issues the patent it is indifferent between doing so or not.

Since a specific maximum permit price is necessary to implement the static first best, the government strictly prefers the flexible scheme over plain permits. Taxes are also not able to achieve the static first best. Due to constant returns to scale either one technology is used exclusively or if firms are indifferent, a random mix of technologies results.

Proposition 19.1 *Assume the established technology is polluting and the new one is socially desirable and clean but not strictly superior and the government can set a permit quantity and a maximum permit price and has no revenue objective. Then the government strictly prefers the flexible instrument over both taxes and plain permits. In the unique subgame perfect equilibrium research incentives are zero as the patent holding firm would be completely expropriated.*

19.2 With Revenue Objective

If $\lambda > 0$, an increase in $\overline{\tau}$ results in an increase in the equilibrium permit price which augments public revenue. The government therefore faces a trade-off between raising public funds and implementing the static optimal allocation. Formally, $\frac{\partial G}{\partial \overline{\tau}} = -\frac{\partial W}{\partial \overline{\tau}} + \lambda E$. Hence, there is a threshold level $\hat{\lambda}$ such that for all $\lambda > \hat{\lambda}$ it holds that $\frac{\partial W}{\partial \overline{\tau}}\big|_{\overline{\tau}=0} < \lambda E$. Research incentives are zero for all $\lambda \leq \hat{\lambda}$ and positive and increasing in λ for all $\lambda > \hat{\lambda}$. Note that $\hat{\lambda}$ is decreasing in c_2 because the optimal E is decreasing in c_2 (Figure 19.1). Hence, the cheaper and therefore the more desirable the new technology, the higher the threshold level $\hat{\lambda}$ necessary to trigger research.

Proposition 19.2 *If assumptions of Proposition 19.1 hold but the government has a revenue objective, it effectively expropriates the patent holding firm if the weight of the revenue objective is at or below $\hat{\lambda}$. For $\lambda > \hat{\lambda}$ there is a unique subgame perfect equilibrium where research incentives are positive and increasing in the weight of the revenue objective.*

Here, in the absence of commitment, a revenue objective can be essential in restricting predation by the government. The aim of the government to achieve static efficiency that spoils research incentives is counterbalanced by its desire to raise revenues. Note that an increase in the upper price bound on permits increases revenues only due to monopoly pricing. Hence, if $\lambda > \hat{\lambda}$ the government is no longer indifferent between granting patents or not. It strictly prefers patents to be granted at the beginning of the post-innovation period.

This analysis might suggest that increasing the revenue objective of the government might be a good idea. However, this is more costly than apparent in this partial equilibrium model. If it is caused by distortionary taxation elsewhere in the economy, raising λ requires to escalate these inefficiencies.

In this setting, patents alone are insufficient in creating research incentives even if they are credible and rule out any form of imitation. Additional interventions, such as R&D subsidies, are essential to create private research incentives for this type of innovation.

Chapter 20

Clean Industry and Polluting Substitute

This chapter analyzes the case of a clean industry (i.e. $a_1 = 0$) facing entry by a polluting technology ($a_2 = 1$). Assume that the new technology is socially desirable but not strictly superior to the established one (see Figure 20.1). $c_1 > c_2$ is a necessary but not a sufficient condition for this to hold.

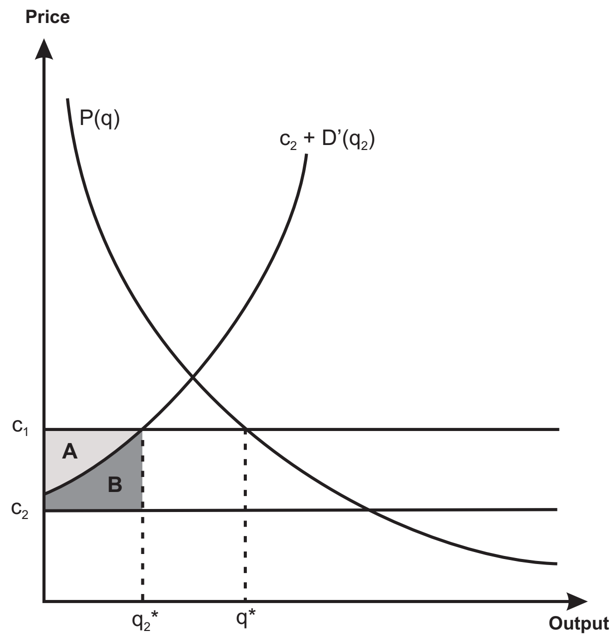

Figure 20.1: A cheap but polluting substitute

20.1 No Revenue Objective

Prior to innovation only technology 1 is available. Optimal output is given by $P(q) = c_1$ and is supplied by the established technology. After successful innovation, technology 2 is available. First best aggregate output is still given by $P(q) = c_1$ but a mix of technologies is optimal.

The equilibrium of the market clearing stage is given by

$$\begin{aligned} P(q) &= c_1, && (20.1) \\ P(q) &= c_2 + \underline{\tau} + \beta + f, && (20.2) \\ q_2 &\leq E, && (20.3) \end{aligned}$$

where β is the equilibrium permit price *on top* of the reservation price $\underline{\tau}$. The reservation price is sufficient to establish the result and hence the upper bound on the permit price is ignored to save on notation. Equations (20.1)-(20.3) determine aggregate output q, the mix of technologies q_1, q_2 and the additional equilibrium permit price β.

In the previous stage the research firm faces a residual demand function

$$\tilde{q}_2(f) = \begin{cases} 0 & : \ f > c_1 - c_2 - \underline{\tau} \\ E & : \ f < c_1 - c_2 - \underline{\tau} \\ (0, E) & : \ f = c_1 - c_2 - \underline{\tau} \end{cases} .$$

The firm just undercuts the threshold by setting a license fee of $f = c_1 - c_2 - \underline{\tau} - \epsilon$, where ϵ is arbitrarily small.

In the first stage the government decides on the policy variables E and $\underline{\tau}$. Given that the new technology is socially desirable but not strictly superior, it holds that $0 < E < P^{-1}(c_1)$. The government's objective function reduces to

$$G(E, \underline{\tau}) = (c_1 - c_2)E - D(E_2) + \lambda \underline{\tau} E. \qquad (20.4)$$

Given $\lambda = 0$ this is independent of the reservation price on permits. Hence, any $\underline{\tau} \in [0, c_1 - c_2]$ implements the static first best. Since $\underline{\tau} = 0$ is included in this set, the government is indifferent between the flexible scheme and plain permits.

The social gain from innovation is equivalent to the shaded area A in Figure 20.1 while research incentives are in the range from 0 to $A + B$ depending on $\underline{\tau}$. Hence, optimal as well as over and under supply of research is possible under the flexible scheme. Plain permits induce excessive research incentives of size $A + B$.

A tax on emissions is not able to implement the static first best allocation. With constant returns to scale either one technology will be strictly preferred or, if effective marginal costs are the same, technologies are randomly mixed.

Proposition 20.1 *Assume the established technology is clean and the new one is socially desirable and polluting but not strictly superior and the government can set a permit quantity, a minimum permit price and has no revenue objective. Then the government is able to implement the static first best both by plain permits and the flexible instrument. Plain permits induce excessive research while under the flexible scheme optimal as well as over and under supply of R&D is possible.*

Here, commitment is much less of a problem than in the previous chapters. Static and dynamic efficiency are no longer mutually exclusive. The first best allocation (static and dynamic) is implemented by a feasible reservation price that induces research incentives of size A. Time-consistency is purely a problem of equilibrium selection. Hence, a pure coordination instrument can serve as a credible commitment device. The same applies to the decision to grant patents.

20.2 With Revenue Objective

If $\lambda > 0$, equation (20.4) is linear and increasing in $\underline{\tau}$. Hence, the optimal reservation price is $\underline{\tau} = c_1 - c_2 - \epsilon$. Regardless of the weight of the revenue objective, the license fee is driven down to zero. The successful research firm does not make any profits and anticipating expropriation the research sector will not engage in R&D in the first place.

Proposition 20.2 *If assumptions of Proposition 20.1 hold but the government has a revenue objective, it is able to implement the preferred allocation using the flexible instrument only. The patent holding firm would be expropriated and hence private research incentives are zero.*

In this case the revenue objective jeopardizes research incentives. By increasing λ it becomes more difficult to achieve commitment on environmental policy. However, commitment on patents is again not an issue. The government does not object to grant them.

Chapter 21

Implementation of the Optimal R&D Policy for Multiple Green Horizontal Innovations

As in the previous part, the endogenous and more flexible design of environmental regulation has first been studied in a two period, two technology setting. In this chapter the insights are applied to the multiple technology, continuous time decentralized economy of part I and chapter 14. This allows the joint implementation of the first best pollution and research policies.

In order to achieve this it has to be assumed that the government is able to commit to future environmental policies if and only if they do not create time-inconsistencies. This is a very weak form of commitment since it merely allows to pre-select one of several options that all yield the same welfare. This degree of commitment is compatible with closed loop equilibria, since time-inconsistency of equilibrium strategies is ruled out. However, it is restrictive in a sense that it eliminates an infinite set of other closed loop equilibria that would occur in the absence of this commitment assumption.

Chapter 14 described the pollution policy that implements the social optimum given a number of technologies n and their status of protection. The second crucial part of an implementation strategy is to ensure that the right amount of private research incentives are created at the desired points in time (and only at these points). Research incentives at time t_n are given by the expected present value of revenues A generated by an additional technology

$$A_n(t_n) = E\left[\int_{t_n}^{\infty} e^{-rt} f_n(t) q_n(t) dt\right]. \tag{21.1}$$

In order for the research pattern induced by the policy to be optimal the following condition has to be met

$$A_n(t_n) = R, \quad \text{if and only if} \quad t_n = t_n^*, \quad \forall n = 2, ..., N. \tag{21.2}$$

21.1 Perfectly Elastic Demand *cum* Capacity Constraint

In the case where the demand function is perfectly inelastic, implementation of the optimal R&D program is feasible given the optimal pollution policies and the ability of the government to commit on one of several (ex-post) payoff equivalent paths. If the government is restricted to use only either a price or a quantity instrument on each pollutant and hence technology, the expected gain from the $n+1^{st}$ technology is

$$A_n(t_n) = E\left[\int_{t_{n+1}^*}^{\infty} e^{-rt} q_{n+1}^*(t)\tau_1(t)dt\right]. \tag{21.3}$$

This gives only one choice variable, the tax rate on the unprotected technology τ_1, to determine the research incentives of $N-1$ technologies. The system is therefore overdetermined. In general, a such constrained implementation strategy does not achieve the socially optimal research trajectory.

Proposition 21.1 *In general, the optimal pollution and research trajectories derived in chapters 4 and 5 can not be implemented in a decentralized economy using only pure emission taxes, permits and patents.*

However, in principle there is nothing to rule out that each pollutant is regulated both by a price and a quantity instrument. Permits might be sold at a reservation price or be subject to a (potentially negative) tax. Allowing for such hybrid schemes the first best research program becomes feasible.[1] The expected present value of technology $n+1$ is now

$$A_n(t_n) = E\left[\int_{t_{n+1}^*}^{\infty} e^{-rt} q_{n+1}^*(t)(\tau_1(t) - \tau_{n+1})dt\right]. \tag{21.4}$$

Hence, there are N choice variables and $N-1$ conditions (see (21.2)), leaving one degree of freedom. The additional price instruments introduced are used to fine

[1]This works only if the government has no revenue objective and the marginal costs of public funds are zero. Otherwise, there is a trade-off between creating research incentives and efficiency losses due to distortionary taxation elsewhere in the economy. Moreover, even the second best policy requires credible commitment in order to overcome the time-inconsistency of giving (or not taking) money to (from) the patent holding firm at a stage where innovation has already occurred. See chapter 20 for a discussion of these issues.

tune the research incentives of each technology without affecting the allocation of output. Note that the optimal set of τ_i's might involve both taxes and subsidies on pollution. Since any $\tau_i < \min[\tau_1, 1]$ does not affect output but only the license fee f_i on technology i the government's commitment requirement satisfies the weak condition specified above.[2] It is merely a pre-selection of one of several (ex-post) payoff equivalent policies.

Proposition 21.2 *The optimal pollution and research trajectories derived in chapters 4 and 5 can be implemented in a decentralized economy using hybrid tax-subsidy-permit schemes and patents.*

Conventional policies to adjust research incentives such as patent length are not sufficient to achieve the first best allocation. Even with an infinite lifetime the incentives created by patents might not suffice to trigger R&D at the optimal point in time. A feasible alternative to the hybrid tax-permit scheme proposed are discriminatory taxes and subsidies on the patent holders revenues combined with standard tax and permit regulation.

21.2 Downward Sloping Demand Function

As indicated in chapter 14 there are fewer degrees of freedom left after implementing the optimal output mix at each point in time, given the number of technologies. More specific, the tax rate on the initially available and competitive technology 1 is uniquely defined at each point in time. This directly results from the effect any license fee choice by a patent holding firm has on output. Hence, by the very nature of a downward sloping demand function prices and quantities are no longer independent of each other. The tax rate on the competitively operated technology 1 is $\tau_1(t) = P\left(Q^*(t)\right)$ at each point in time. Hence, (21.4) becomes

$$A_n(t_n) = E\left[\int_{t^*_{n+1}}^{\infty} e^{-rt} q^*_{n+1}(t)\left[P\left(Q^*(t)\right) - \tau_{n+1}\right] dt\right], \tag{21.5}$$

if the demand function is downward sloping. Plugging this into conditions (21.2) the resulting system is exactly determined.

Proposition 21.3 *Pollution and research trajectories as derived in chapters 4 and 5 can be implemented using hybrid tax-subsidy-permit schemes and patents in a decentralized economy with a downward sloping demand function and without a capacity constraint on aggregate output.*

[2] The upper bound is due to the marginal benefit of production being equal to one.

Note that for a backstop technology $P(Q^*(t)) = 0$ for all $t \geq t_n^*$. Moreover, there is no pollution that could be subsidized.[3] Hence, a perfectly clean technology does not create any private incentives for R&D although it is the socially most desirable outcome. This reflects the basic trade-off between static efficiency and the creation of research incentives by granting patents and hence monopoly power. If the new technology creates pollution externalities there is some scope to align the two issues since up to a certain point both market failures call for a reduction in output. A price above private marginal costs is socially optimal and the revenues can be channeled to patent holders. With perfectly clean technologies this is impossible (Laffont and Tirole 1996b, Denicolò 1999). However, since it is assumed that a research firm has no influence on the arrival probability of a backstop p implementation of the optimal research trajectory is still feasible if $p < 1$. Revenues generated by a boomerang technology have to be sufficiently high so that conditions 21.2 can still be met as is ensured by (21.5).

Credibility of patents is not an issue in this situation. The optimal pollution policy ensures that the market power of patent holding firms does not distort output decisions. Hence, after innovation has occurred the government is indifferent between granting a patent and not granting it. The weak form of commitment assumed above is therefore sufficient to implement the optimal research trajectory.

Note that so far no explicit solutions for a socially optimal pollution and research policy for a problem similar to the on presented in part I exist for the case with a downward sloping demand function. However, their qualitative features derived in chapter 14 are sufficiently to establish that implementation is feasible using the strategy described above.

[3] Subsidizing output instead would distort entry and exit decisions.

Chapter 22

Conclusion of Part III

Real world environmental policies are often more complex than a glance at the existing literature on instrument choice might suggest. Permit schemes involve auctions with reservation prices, fixed penalties for excessive emissions and are complemented by taxes. Extending the choice set of the government to take this into account enhances its ability to achieve post-innovation static efficiency. However, since static efficiency contradicts monopoly pricing by a patent holding firm, research incentives often decrease if instrument design is endogenous. In some cases flexibility in instrument design results in full expropriation of intellectual property. A lack of commitment on details such as auction rules, penalties or the set up of a complimentary tax scheme, on the one hand, can therefore pose a serious threat on the effectivity of patents in stimulating private research.

On the other hand, a more flexible tax-subsidy-permit scheme is able to implement the first best R&D policy for multiple green horizontal innovations. This applies both to the case with a perfectly elastic demand function with a capacity constraint and to a situation with a downward sloping demand function. Hence, the optimal pollution and R&D trajectories derived in part I can be implemented in a decentralized economy.

Moreover, standard welfare maximization is not necessarily the sole objective of a government. The public funds raised by environmental regulation are sometimes treated as a value in its own right. Such a revenue objective of the government affects private research incentives in very different ways. R&D efforts can be increasing in the weight of public funds, which e.g. is the case with vertical environmental innovation. A certain threshold weight might even be a prerequisite for the existence of research incentives. However, a revenue objective is not proposed as a solution to under provision of R&D. First, it can trigger expropriation of the patent holding firm for other types of innovation and second, raising the weight of the revenue objective is feasible only by inducing additional distortions elsewhere in the economy.

When environmental policy is endogenous, patent law itself does usually not face a time-inconsistency problem. The government is at least indifferent to grant intellectual property rights or might even be strictly in favor to do so ex-post. The entire time-inconsistency is concentrated in environmental regulation. The case of vertical innovation with revenue objectives is the only exception where a commitment on patent law is relevant.

The next part aims to shed some light on how a sovereign government is able to make credible commitments. In addition, instruments that do not face the problem of time-inconsistency, such as R&D subsidies, might be able to provide alternative means to solve this kind of problem.

Part IV

Commitment by Delegation

Chapter 23

Introduction to Part IV

Time-inconsistency features prominent in many policy areas.[1] For a sovereign credible commitment is especially hard to achieve, since by definition she has discretionary scope that cannot be restricted. She can change any law or constitutional amendment she passes at later stages. This is in line with rule of law and merely reflects that the sovereign has the authority to legislate.

Several solutions to the time-inconsistency problem have been proposed. Trigger strategies (Barro and Gordon 1983), reputation (Barro 1986) and delegation (Rogoff 1985) are most prominent. In this part the focus is on the latter, which is popular in monetary economics, is supported by empirical evidence (Berger et al. 2001) and is also being considered in other policy areas (Levine et al. 2005, Roelfsema 2007).

McCallum (1995, 1997) formulated a fundamental criticism to the idea that delegation increases commitment. *"The problem [...] is that such a device does not actually overcome the motivation for dynamic inconsistency; it merely relocates it."* (McCallum 1995, p. 210) Instead of committing to the policy itself the sovereign has to commit to an institution, since sovereignty implies the power to remove delegation or override a bureaucrat's decision.[2] Delegation is not credible by definition but the level of independence or accountability of a bureaucrat depends on the degree of commitment the sovereign attributes to the institution. McCallum therefore

[1] E.g. monetary policy (Kydland and Prescott 1977, Barro and Gordon 1983), utility regulation (Gilbert and Newbery 1994), trade policy (Staiger and Tabellini 1987), political economy (Besley and Coate 1998, Acemoglu 2003) and environmental regulation (see chapters 19, 20 and Laffont and Tirole (1996b)).

[2] See Balla (2000) and McCubbins and Schwartz (1984). The latter write: *"The problem [with delegation] is that the bureaucracy might not pursue Congress's goals. [...] Then Congress can intervene to rectify the violation. Congress has not necessarily relinquished legislative responsibility to anyone else. It has just found a more efficient way to legislate."* (p. 175)

regards it a fallacy to discuss time-inconsistency only for specific policies but not in the context of institutions. Either a commitment device exists and hence the sovereign can commit to either of them, or it does not, in which case commitment is feasible for neither of them. Unless there is something that makes changes in institutions fundamentally different from any other decision by the sovereign, this seems to contradict the validity of delegation as a commitment device.[3]

This part formalizes McCallum's critique. Both a specific policy and the institutional structure are subject to the same commitment technology that allows for an endogenous level of credibility. McCallum's '*second fallacy*' is confirmed in a complete information setting. However, if there is a trade-off between flexibility and credibility due to exogenous shocks affecting the state of the economy, delegation is able to relax this trade-off if the bureaucrat's response to a shock is at least somewhat in line with sovereign's preferences. This effect induces the sovereign to invest more in credibility under delegation. Hence, while delegation does not increase commitment *per se* it makes credibility more attractive. The observed commitment effect of delegation can therefore be explained even if the commitment technologies for delegation and discretionary regulation are identical as is the case in lawmaking by a sovereign. McCallum's critique does not hold in this case.

Hence, the present part establishes gains from delegation although it abstracts from asymmetric information between the sovereign and the bureaucrat. Alesina and Tabellini (2007a,b) and Ludema and Olofsgard (2007) investigate effects arising from the interaction between asymmetric information and time-inconsistency.

However, like most contributions on the commitment effect of delegation[4], they take its credibility for granted. Exceptions are Lohmann (1992), Jensen (1997), Moser (1999) and Keefer and Stasavage (2003). In Jensen (1997) commitment is provided by tit-for-tat punishment strategies in a repeated game. He shows that delegation has no effect on credibility of policies if overriding is costless. However, if changes in policies set by an agency are costly (and increasingly so in the size of the adjustment) then time-inconsistency can be partially resolved. However, the degree of commitment, defined as the set of discount factors that support optimal monetary policy is reduced, since punishment is less severe. Jensen (1997) concludes that delegation diminishes commitment. Recently, Driffill and Rotondi (2006) showed that the opposite holds if more general incentive contracts for central bankers are consid-

[3]For reasons such differences might exist see Lohmann (2003).

[4]See e.g. Rogoff (1985), Walsh (1995), Maskin and Tirole (2004), Levine et al. (2005).

ered. However, the differences in the costs of overriding a policy set by the sovereign compared to one set by an agency are somewhat *ad hoc* and seem hard to defend in general. Overriding delegated policies might even be easier if the bureaucrat acts as a 'scapegoat' (Fiorina 1982, Alesina and Tabellini 2007b).

Moser (1999) and Keefer and Stasavage (2003) use heterogeneous veto players to induce commitment and find that delegation enhances credibility. They take the initial level of commitment both to the policy as well as to the institutional design as exogenously given. Hence, the effect present in their papers is complementary to the one established here since the latter requires at least some discretion of the sovereign with respect to the initial level of commitment that might involve but does not depend on multiple veto players. The discretion over the level of commitment, that is crucial for the following results, stems from the ability of a sovereign to influence the costs involved in future policy changes, e.g. by setting different majority rules.

Lohmann (1992) provides an analysis of monetary policy where the sovereign has control over the level of commitment represented by the cost incured to adjust the policy ex-post. However, she does not explicitly solve the optimal policy without delegation and, in contrast to the present part, does not treat commitment as an investment.

There is also a link to formal and real authority as discussed by Aghion and Tirole (1997). Here, as in their model, the sovereign has formal and real authority in the case of discretion. However, if she delegates she keeps formal authority but at least in some cases real authority rests with the agent. In contrast to Aghion and Tirole (1997), it is not asymmetric information but the desire to commit that drives the institutional structure. Moreover, in this part, delegation is not modeled as a binary choice to transfer formal authority but the sovereign can choose the degree to which she relinquishes authority.

This part presents a solution to the puzzle of how delegation can improve commitment. It combines two features: an endogenous level of commitment in the form of a policy adjustment cost and a bureaucrat that reacts to exogenous shocks to the state of the economy. It is shown that even if credibility of delegation is provided by the same commitment technology as for any other policy (i.e. McCallum's basic assumption holds), a sovereign invests more in commitment if she delegates. Hence, delegation is associated with higher levels of commitment than policies set directly by the sovereign.

The mechanism driving this result is as follows. Without delegation, an increase in the level of commitment by a sovereign inherently raises the costs to adjust a policy ex-post. Accommodation of exogenous shocks is therefore imperfect and creates a trade-off between credibility and flexibility. However, with delegation and a bureaucrat whose response to such shocks is at least somewhat in line with that desired by the sovereign this trade-off is less severe. Although the commitment technology is the same, the sovereign invests more in credibility if she delegates than if she sets the policy herself.

Hence, the demand for flexibility to adjust to exogenous shocks is crucial for delegation to a bureaucrat to be desirable. This contrasts recent results by Alesina and Tabellini (2007b) and Ludema and Olofsgard (2007). They find that when flexibility is valuable the politician (here: sovereign) is preferred over the bureaucrat to carry out the task. The difference in results originates from the way commitment and delegation are modeled. Alesina and Tabellini (2007b) and Ludema and Olofsgard (2007) rule out ex-post overriding of a bureaucrat's decisions and do not consider commitment by the sovereign. The endogenous degree of independence or accountability of the bureaucrat and the symmetry of the commitment technology with respect to both institutions and specific policies are key features of the present part.

The remainder of this part is organized as follows. The baseline model is set up in the next chapter. Chapter 25 formalizes McCallum's '*second fallacy*'. In chapter 26 the model is extended to a repeated game with some exogenous shock occurring between periods. This is shown to be sufficient to establish a higher level of commitment associated with delegation, even if it is costly to delegate. The last chapter concludes this part.

Chapter 24

The Model

In this chapter the deterministic baseline model is presented. The issue at hand is the choice of a one-dimensional policy variable p such as an interest rate, a tax or a tariff. Three agents are involved in the policy game: a sovereign, a subject and a bureaucrat. The sovereign holds the power to pass and change regulations, laws and amend the constitution and thereby determine both institutions and the specific policy. For simplicity she is modeled as a single agent, although one best thinks of her as a parliament. The subject is anyone who is not directly involved in policy making but affected by the policy under concern. The bureaucrat is a person appointed by the sovereign to perform a specific task with at least some discretionary scope.

The timing of the game is as follows (see Figure 24.1). First, the sovereign decides whether to delegate the policy task to the bureaucrat and in the case of delegation also the level of commitment $c \in [0, \infty)$.[1] The latter is defined by the cost to codify the policy which has to be incured for the first time simultaneously to its choice. This reflects that administrative procedures, laws and constitutional amendments require different efforts and majorities to be passed. The costs of decision making by a sovereign are potentially substantial. One reason is that at least in some cases the number of people involved is quite large, the other reason is that a sovereign is the prominent political authority and hence responsible for all policy areas. Due to capacity constraints she can not attend to all potentially beneficial reforms but has to set a political agenda. The cost of writing a particular law therefore includes the opportunity cost of the gain not realized by pursuing a reform in a different policy area. Moreover, this cost is a commitment device since at the same time it specifies

[1] If the sovereign delegates, $c = 0$ corresponds to the case of 'integration' and $c \to \infty$ to the case of 'full delegation of formal authority' in Aghion and Tirole (1997).

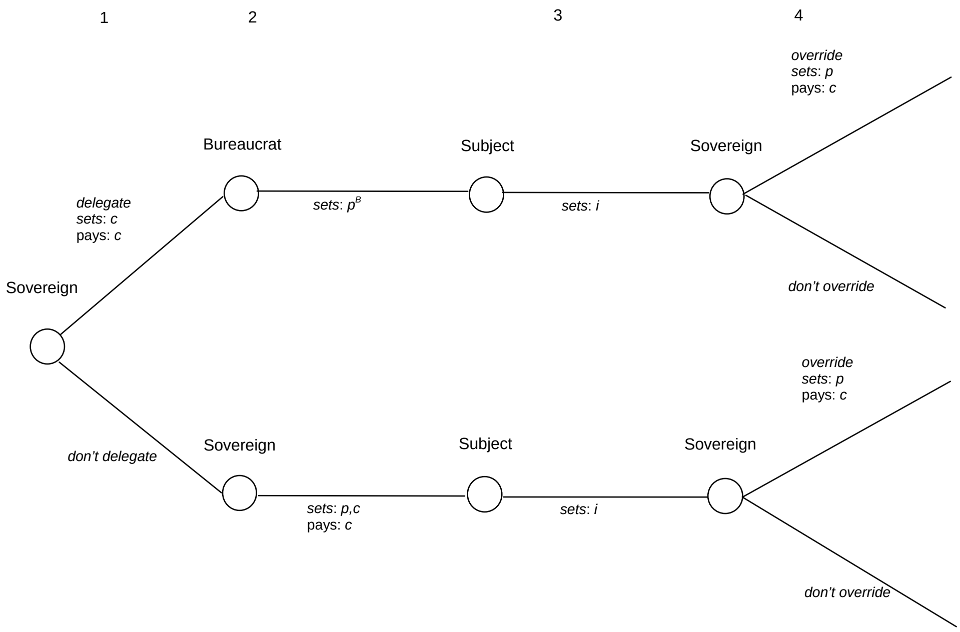

Figure 24.1: Timing of the game

the minimum cost to adjust the policy at a later stage.[2] Second, depending on the institutional choice in the first stage, either the sovereign or the bureaucrat sets the policy level p. In the case of discretionary policy setting by the sovereign, she also chooses (and incurs) c. Third, the subject forms expectations about the policy level actually implemented and takes an irreversible decision, e.g. an investment or signing of a long term contract. Fourth, the sovereign is able to adjust the policy level under both delegation and discretion by again incuring c. Finally, payoffs of all players realize.

Note that the bureaucrat's decision costs are normalized to zero. This might be perceived as a rather strong assumption. However, the basic point is that a sovereign is able to impose decision costs onto herself that exceed that of a bureaucrat. While the sovereign can choose zero decision cost for herself this turns out not to be optimal due to the time-inconsistency problem. The only asymmetry between the two players with respect to decision costs is that the bureaucrat can not raise his own costs. However, since by definition he is not prone to time-inconsistency nothing is gained by giving him this option.

[2]It is thereby assumed, that both the technology and opportunity costs of decision making are constant over time.

In contrast to earlier contributions (Lohmann 1992, Jensen 1997, Keefer and Stasavage 2003) commitment is an investment. Besides a loss in flexibility it is inherently costly to commit. This makes an endogenous level of commitment interesting even in the deterministic one period game of chapter 25.[3]

The sovereign has the following objective function with respect to the policy problem under concern

$$w(p, i(p)), \tag{24.1}$$

where p is the policy implemented, c is the costs of an ex-post adjustment of p and $i(p)$ is the best response of the subject to the policy p. The one shot game depicted in Figure 24.1 is therefore a game of complete information. Let

$$v(p) \tag{24.2}$$

be the reduced form of (24.1), with $\frac{\partial v}{\partial p} = \frac{\partial w}{\partial p} + \frac{\partial w}{\partial i}\frac{\partial i}{\partial p}$ and $\frac{\partial^2 v}{\partial p^2} < 0$, where $\tilde{p}^*$ is the unique optimal ex-ante policy that maximizes both (24.2) and (24.1).

However, given the subject's decision is already fixed, the sovereign's objective function is

$$\hat{v}(p, p^E), \tag{24.3}$$

where $\frac{\partial \hat{v}}{\partial p^E} = \frac{\partial w(p,i)}{\partial i}\frac{\partial i(p^E)}{\partial p}$, $\frac{\partial^2 \hat{v}}{\partial p^2} < 0$ and $\frac{\partial \hat{v}}{\partial p} = \frac{\partial w(p,i)}{\partial p}$. $p^E(p, c)$ is the subject's expectation with respect to the policy actually implemented in stage 4. The unique optimal ex-post policy is $\hat{p}^*$. Note that if the subject's expectations turn out to be correct, (24.2) and (24.3) coincide, i.e. $v(p) = \hat{v}(p, p)$. If $\frac{\partial w}{\partial i}\frac{\partial i}{\partial p} \neq 0$ the optimal ex-ante and ex-post policies differ and the sovereign faces a time-inconsistency problem. Without loss of generality assume that $\frac{\partial w}{\partial i}\frac{\partial i}{\partial p} > 0$ and hence, $\hat{p}^* < \tilde{p}^*$.

Assume for a moment that the sovereign is unable to commit and delegation is not feasible. Ex-ante she is keen to promise a policy level of $\tilde{p}^*$. However, the subject anticipates that for $p^E = \tilde{p}^*$, she implements $\hat{p}^* < \tilde{p}^*$ ex-post. Implementing $\tilde{p}^*$ in the fourth stage is not subgame perfect and hence, the second stage promise to do so not credible. In the subgame perfect equilibrium, the subject's expectations turn out to be correct and hence $p^E = \hat{p}^*$.

Considering the full game with commitment and delegation, the bureaucrat's preferences and constraints become relevant. The bureaucrat is best thought of as

[3]Lohmann (1992) and Keefer and Stasavage (2003) consider stochastic games while Jensen (1997) has an exogenous cost of policy adjustments.

the director or board of a specialized agency. The agency itself would be needed to implement and enforce the policy anyway. Delegation implies that it also gets a clearly defined discretionary scope. The bureaucrat's objective function is

$$g^B = \begin{cases} g\left(p^B\right) & , \quad p^B \text{is credible,} \\ 0 & , \quad \text{else,} \end{cases} \tag{24.4}$$

where $g(p^B)$ has a unique global maximum at the optimal ex-ante policy level $\tilde{p}^*$ and is strictly monotone both to the left and the the right of this peek. Moreover, $g(p^B) > 0$ for all p^B. Hence, in this deterministic setting it is assumed that the sovereign can perfectly determine the preferences of the bureaucrat and hence chooses them to match her ex-ante objective. This is implemented by means of administrative procedures or incentive contracts (Walsh 1995). However, this assumption is relaxed in latter chapters where uncertainty becomes relevant and the sovereign's control over the bureaucrat's responses to such unforeseen events will be imperfect.

In addition, the bureaucrat does not like to be overridden by the sovereign. This is regarded a strong signal that he failed to do his job properly and thereby diminishes his future career and earning abilities. Sovereignty is not restricted by delegation since the sovereign is able to override the bureaucrat before the policy is actually implemented.[4]

The next chapter analyzes policy choices in this baseline model. A repeated game with uncertainty over the future state of the world is considered in chapter 26.

[4]See also Lohmann (1992), Jensen (1997), Aghion et al. (2004).

Chapter 25

McCallum's Second Fallacy

In this chapter it is shown that in the complete information model presented above equilibrium commitment is positive and McCallum's second fallacy holds. The timing of events is as outlined in Figure 24.1. It is assumed that there is no history in the relevant policy area.

25.1 Discretion

First consider the case where the sovereign does not opt for delegation. Given the policy, p and the commitment level, c, set in stage 2 she adjusts the policy in stage 4 if and only if the following condition holds

$$\hat{v}(\hat{p}^*, p) - \hat{v}(p, p) > c. \tag{25.1}$$

This is equivalent to $\hat{v}(\hat{p}^*, p) - v(p) > c$. Hence, for all $p < \underline{p}(c)$ and $p > \bar{p}(c)$ adjustment occurs while all $p \in [\underline{p}(c), \bar{p}(c)]$ are credible, where $\underline{p}(c)$ and $\bar{p}(c)$ are determined by

$$\hat{v}(\hat{p}^*, p) - v(p) = c. \tag{25.2}$$

The costs to adjust the policy ex-post determines the set of credible policies. This is in line with Lohmann (1992) and Jensen (1997).

In the third stage, subjects decide on i according to their expectations of the policy implemented that are as follows

$$p^E = \begin{cases} p & , \quad p \in [\underline{p}(c), \bar{p}(c)], \\ \hat{p}^* & , \quad \text{else.} \end{cases} \tag{25.3}$$

In the second stage the sovereign chooses both p and c simultaneously

$$\max_{p,c} L^{Dis} = v\left(p^E(p, c)\right) - c. \tag{25.4}$$

Since L^{Dis} is strictly decreasing in c unless $p^E = \underline{p}(c)$ or $p^E = \bar{p}(c)$ the credibility constraint is always binding. Moreover, since $\hat{p}^* < \tilde{p}^*$ it is the upper bound that binds. The optimal c and hence $\bar{p}(c)$ is determined by

$$\frac{\partial v(p)}{\partial p}\frac{\partial \bar{p}(c)}{\partial c} = 1. \tag{25.5}$$

Total differentiation of (25.2) and plugging into (25.5) yields

$$-\frac{\frac{\partial v}{\partial p}}{\frac{\partial \hat{v}}{\partial p}} = 1, \tag{25.6}$$

which yields c^* and hence $p^* = \bar{p}(c^*) < \tilde{p}^*$.

Proposition 25.1 *If commitment is a costly investment, the optimal level of commitment depends on the marginal gain from credibility and is at most partial.*

Proof. See appendix.□

Here, partial commitment means that in equilibrium the sovereign invests a non-negative, finite amount in credibility and the policy level p^* is strictly below the 'full' commitment solution. Note that, in contrast to quasi-commitment discussed by Schaumburg and Tambalotti (2007), partial does not imply that the sovereign reneges in some cases. Since the one period game is deterministic, partial commitment merely reflects the investment character of commitment.

25.2 Delegation

Now consider the case with delegation. Stages 3 and 4 of the game are as analyzed above. In the second stage the bureaucrat chooses the policy anticipating the subject's decision and the set of credible policies. Given the properties of the bureaucrat's objective function $g^B(p^B)$, the policy level chosen by the bureaucrat is either $p^B = \tilde{p}^*$ if this is credible, i.e. $\tilde{p}^* \in [\underline{p}(c_1), \bar{p}(c_1)]$, or $p^B = \bar{p}(c_1)$ otherwise. Since the policy choice of the bureaucrat perfectly mirrors the ex-ante preferences of the sovereign, the only difference to the case of discretion is the timing. While under discretion c and p are set simultaneously, they are chosen sequentially here. However, this does not affect the optimality condition. The equilibrium values are exactly the same as without delegation (see (25.6)), i.e. yield c^* and p^*.

Proposition 25.2 *In a deterministic game a sovereign is indifferent between delegating a policy task and full discretion. Delegation does neither affect commitment nor the payoff of the sovereign or the subject.*

Since the subgame perfect policies of both delegation and discretion are equivalent, the sovereign is indifferent between both institutional designs. This confirms the fundamental insight of McCallum's second fallacy that delegation does not solve the commitment problem but merely relocates it. Neither the ability nor the desire of a sovereign to commit is improved by delegation.

In a deterministic game the equivalence of delegation and discretion breaks down only if for some reason the commitment technologies for delegation and discretionary policy making differ. The next chapter shows that, with symmetric commitment devices, the equivalence also breaks down if a flexibility-credibility trade-off is considered.

Chapter 26

Beyond the Fallacy

In contrast to the previous chapter, now the policy game is played more than once. However, in order to avoid to import some credibility by folk theorem type arguments the number of repetitions N is assumed to be finite. In fact, to derive the main results it is perfectly sufficient to look at the case of $N = 2$. Extension to $N > 2$ is straightforward. Moreover, reputation effects are ruled out. Both assumptions are imposed to keep the focus of the analysis on the effect of delegation and are by no means meant to imply that the former effects do not matter in the real world. However, the results of this chapter suggest that there is a complementary mechanism at work by which delegation becomes associated with improved credibility.

If the game is played twice, there is a history in the second round. Periods are indicated by subscripts. The policy p_1, the costs to adjust the policy c_1 and not least the institutional structure itself chosen in the first round are inherited to the second one. Hence, if the sovereign prefers a change in any parameter (including $c_2 < c_1$), this costs c_1 in the first stage of period 2.

Moreover, between the two rounds, the state of the world changes which is reflected by $v_2(p - s)$. This can either be due to an exogenous shock to the economy or to the sovereign's ex-ante preferences. This results in a change of the preferred ex-ante policy from $\tilde{p}_1^*$ to $\tilde{p}_2^* = \tilde{p}_1^* + s$. The distribution of the shock s has a density $\phi(s)$ with a zero mean.

In case the inherited institution is delegation, the shock is assumed to affect the bureaucrat's objective function analogously but dampened by a factor $a \in [0, 1]$. Hence, in contrast to the previous chapter the bureaucrat does no longer perfectly reflect the sovereign's preferences in all states of the world. More specifically a bureaucrat of type a maximizes the following objective function

$$g_2^B = \begin{cases} g_2\left(p^B - as\right) & , \quad p^B \le \bar{p}(c_1), \\ 0 & , \quad \text{else}, \end{cases} \tag{26.1}$$

where g_2 differs from g_1 due to the exogenous shock s. More precisely, the bureaucrat sets the second period policy according to

$$p_2^B(c_1, a, s) = \begin{cases} \bar{p}(c_1) & , \quad \tilde{p}_1^* + as > \bar{p}(c_1), \\ \underline{p}(c_1) & , \quad \tilde{p}_1^* + as < \underline{p}(c_1), \\ \tilde{p}_1^* + as & , \quad \text{else}. \end{cases} \tag{26.2}$$

Note, that $a = 1$ reflects 'perfect' delegation in the sense that the bureaucrat perfectly reflects the sovereign's response to the exogenous shock. The type of the bureaucrat is exogenous but common knowledge at the beginning of the first period. Hence, if $a = 1$, the sovereign anticipates that any shock occurring in the second period will be costless neutralized by the bureaucrat. On the other hand, if $a = 0$, the policy preferred by the bureaucrat remains at $\tilde{p}_1^*$ and hence, delegation and discretion are again equivalent.[1]

26.1 The Final Period

Only stages 1 and 2 of period 2 are analyzed, since stages 3 to 4 are as before. The optimal policy after the shock is derived in what follows.

First, consider the level of commitment. For the second and therefore last period, the optimal commitment level in the absence of any inherited value is c^* (see (25.6)). However, given c_1 it is never optimal to choose a $c_2 < c_1$. It would not reduce adjustment costs but would reduce the benefits of commitment. Moreover, in what follows the analysis is restricted to the cases where $c_1 > c^*$. The case where $c_2 > c_1$ is treated in the appendix and yields the same qualitative results.

Second, consider the optimal policy level p_2. If the optimal ex-ante policy in the second period is credible $\tilde{p}_2^* \in [\underline{p}(c_1), \bar{p}(c_1)]$ it is of course best to implement it, in case adjustment is worthwhile. However, if this is not feasible due to the credibility constraint the best available policy is to choose the credible policy closest to the preferred level, i.e. $p_2 = \underline{p}(c_1)$ if $\tilde{p}_2^* < \underline{p}(c_1)$ and $p_2 = \bar{p}(c_1)$ if $\tilde{p}_2^* > \bar{p}(c_1)$.

The sovereign pursues the reform only if the benefits of regulatory action at least cover its costs (Mulligan and Shleifer 2005). For the case where discretion is the

[1] This corresponds to the situation discussed by Ludema and Olofsgard (2007).

inherited institutional structure, the relevant condition is

$$v\left(p_2(c_1,s)-s\right)-v\left(\bar{p}(c_1)-s\right)>c_1. \tag{26.3}$$

This defines a set of states $\mathcal{S}^{Dis}(c_1)=\left(-\infty,\underline{s}^{Dis}(c_1)\right[$, with $\frac{\partial \underline{s}^{Dis}}{\partial c_1}<0$, where the sovereign intervenes for all $s<\underline{s}^{Dis}$ (proof see appendix). The benefit to change the policy setting from c_1 and p_1 to c_2 and p_2 has to outweigh the costs of doing so. Note that if $s=0$ the sovereign is pleased with the heritage from the previous period. Hence, any incentive of the sovereign to engage in this policy area again is driven by an exogenous change in the state of the world. Note that positive shocks ($s>0$) never induce the sovereign to adjust the policy in the second period, since the best available policy level is $\bar{p}(c_1)<\tilde{p}_1^*$. Hence, the shock has to be sufficiently negative for (26.3) to be met.

If the sovereign has chosen to delegate in the first round, further political action is worthwhile in period 2 if

$$v\left(p_2(c_1,s)-s\right)-v\left(p_2^B(c_1,a,s)-s\right)>c_1. \tag{26.4}$$

This defines a set of states $\mathcal{S}^{Del}(c_1,a)=]\frac{\underline{p}(c_1)-\tilde{p}_1^*}{a},\underline{s}^{Del}(c_1,a)[$ where the sovereign intervenes (proof see appendix).

Remark 26.1 *Interventions are strictly less likely when delegation is the inherited institution, i.e.* $\mathcal{S}^{Del}(c_1,a)\subseteq\mathcal{S}^{Dis}(c_1)$.

Proof. See appendix. □

As in the one period game, in stage 4 the sovereign does not renege on the policy announced. However, at the beginning of the second period the institutional structure or the policy itself might be meddled with by the sovereign. Hence, in contrast to Lohmann (1992), an exogenous shock can trigger an intervention by the sovereign in equilibrium. Note that this type of intervention does not affect time-inconsistency since it happens before subjects form their expectations.

A direct implication of Remark 26.1 is

Corollary 26.1 *The expected payoff in the final period is weakly higher if the policy has been delegated in the past.*

Proof. If $a>0$ and $c_1>0$, then for all $s_2\in I\!R\setminus\mathcal{S}^{Del}(c_1,a)$, the sovereign is (at the beginning of the final period) better off if delegation rather than discretion was the institutional structure in period 1. For all $s_2\in\mathcal{S}^{Del}(c_1,a)$ and if $a=0$ or $c_1=0$, the sovereign is indifferent about the established institutional structure, since the equilibrium policies after intervention are the same (Proposition 25.2).□

26.2 The First Period

In the first round of the two period game, the set of choices and the timing is equivalent to the one shot game in chapter 25. However, incentives and hence optimal policies are different. The expected payoffs of the second period are anticipated and discounted by a discount factor r. This does not affect any of the choices in stages 3 to 4. However, in the first stage (and the second stage in case of discretion), the sovereign faces a more complex optimization problem than in a one shot game. In case she opts for discretion in stage one it is of the following type in stage two

$$\begin{aligned}\max_{c_1} \quad & v(\bar{p}(c_1)) - c_1 + r \cdot \left\{ \int_{-\infty}^{\underline{s}^{Dis}(c_1)} \phi(s) \left[v\left(p_2(c_1) - s\right) - c_1 \right] ds \right. \qquad (26.5)\\ & \left. + \int_{\underline{s}^{Dis}(c_1)}^{+\infty} \phi(s) v\left(\bar{p}(c_1) - s\right) ds \right\}.\end{aligned}$$

Note that $p_1 = \bar{p}(c_1)$.

If the sovereign chooses delegation, the optimization problem in stage one is

$$\begin{aligned}\max_{c_1} \quad & v(\bar{p}(c_1)) - c_1 + r \cdot \left\{ \int_{-\infty}^{\frac{\underline{p}(c_1) - \bar{p}_1^*}{a}} \phi(s) v\left(\underline{p}(c_1) - s\right) ds \right. \qquad (26.6)\\ & \left. + \int_{\frac{\underline{p}(c_1) - \bar{p}_1^*}{a}}^{\underline{s}^{Del}(c_1,a)} \phi(s) \left[v\left(p_2 - s\right) - c_1 \right] ds + \int_{\underline{s}^{Del}(c_1,a)}^{+\infty} \phi(s) v\left(p^B(c_1,a) - s\right) ds \right\}.\end{aligned}$$

Proposition 26.1 *In a repeated game, the sovereign prefers to delegate in the first period, if the bureaucrat is at least somewhat responsive to exogenous shocks and is indifferent between delegation and discretion if not.*

Proof. If and only if $a = 0$, the optimization problems (26.5) and (26.6) are identical and, hence, the sovereign is indifferent between the two institutional structures. If $a > 0$, the payoff of the first period does not depend on the institutional structure directly (Proposition 25.2). However, the expected payoff of the final period is strictly larger when the policy is delegated in the first period (Corollary 26.1). Unless $a = 0$, the sovereign has a strict preference to delegate policy tasks when she faces a time-inconsistency problem.□

Both institutions are again perfectly equivalent if the bureaucrat does not (partially) adjust to the exogenous shock. Hence, McCallum's fallacy holds in the repeated version of the game if $a = 0$. The advantage of delegation stems from the reduction in the trade-off between credibility and flexibility. Bureaucrats of types $a > 0$ provide some flexibility that does not conflict with credibility since it does not involve costly interventions by the sovereign.

Is there an equally unambiguous ranking of institutions with respect to their level of credibility? To answer this question, take the first order conditions of (26.5) and (26.6) with respect to c_1. They yield (using (26.3) and (26.4) that hold as an equality at the threshold levels)

$$\frac{\partial v}{\partial p}\frac{\partial \bar{p}}{\partial c_1} - 1 + r \cdot \left[\int_{-\infty}^{\underline{s}^{Dis}(c_1)} \phi(s) \left[\frac{\partial v}{\partial p}\frac{\partial p_2}{\partial c_1} - 1 \right] ds + \int_{\underline{s}^{Dis}(c_1)}^{+\infty} \phi(s) \frac{\partial v}{\partial p}\frac{\partial \bar{p}}{\partial c_1} ds \right] = 0 \tag{26.7}$$

and

$$\begin{aligned} &\frac{\partial v}{\partial p}\frac{\partial \bar{p}}{\partial c_1} - 1 \\ &+ r \cdot \left[\int_{-\infty}^{\frac{\underline{p}(c_1)-\tilde{p}_1^*}{a}} \phi(s) \frac{\partial v}{\partial p}\frac{\partial \underline{p}}{\partial c_1} ds + \int_{\frac{\underline{p}(c_1)-\tilde{p}_1^*}{a}}^{\underline{s}^{Del}(c_1,a)} \phi(s) \left[\frac{\partial v}{\partial p}\frac{\partial p_2}{\partial c_1} - 1 \right] ds + \int_{\underline{s}^{Del}(c_1,a)}^{+\infty} \phi(s) \frac{\partial v}{\partial p}\frac{\partial p^B}{\partial c_1} ds \right] = 0 \end{aligned} \tag{26.8}$$

respectively. The first terms in both conditions reflect the effect on first period payoffs and hence do not justify any difference in commitment or policy levels in their own right. However, the expected marginal impact of an increase in c_1 on second period payoffs differs across institutions and is unambiguous.

Proposition 26.2 *In a repeated game, the sovereign chooses a (weakly) higher level of commitment in the first period if she delegates than she would, ceteris paribus, if she is restricted to set the policy herself, i.e.* $c_1^{Dis} \leq c_1^{Del}$. *If* $a > 0$, *the level of commitment is strictly larger* $c_1^{Dis} < c_1^{Del}$.

Proof. See appendix □

The intuition is as follows. The exogenous shock occurring between periods makes it desirable to change the policy implemented in the first period. Without delegation the cost for such an adjustment is at the same time the commitment device imposed to reduce time-inconsistency. Hence, the need for flexibility directly conflicts with the desire to commit. With delegation, however, this trade-off is relaxed. Given that the bureaucrat is at least somewhat responsive to the shock, i.e. $a > 0$, there is some accommodation of the new state of the world - at zero costs. Hence, for some shocks, the bureaucrat's reaction is sufficient such that the conflict between flexibility and credibility is reduced. Ex-ante the sovereign does therefore invest more in commitment if she delegates. Note that delegation does not create additional credibility *per se* but creates conditions under which being credible is more attractive.

If the sovereign faces time-inconsistency, delegation of policy tasks is both preferred by the sovereign and associated with higher levels of commitment. This holds although the commitment technologies for delegation and discretionary regulation are perfectly equivalent, reputation is ignored and the time horizon of the sovereign is limited.

26.3 Costly delegation

So far delegation was for free. However, granting discretionary scope to a bureaucrat is likely to be associated with additional costs, e.g. paying skill premiums and more sophisticated hiring processes. This gives rise to an extra cost of delegation payed in each period where delegation is in place.

Adding this cost to (26.6) reduces the attractiveness of delegation. Hence, Proposition 26.1 does no longer hold. Depending on the costs of delegation and the responsiveness of the bureaucrat a either discretion or delegation is the preferred institutional structure. *Ceteris paribus* by an increase in the costs of delegation or a decrease in a delegation becomes less attractive.

However, given that the commitment technology is still the same for both institutional structures, Proposition 26.2 holds. The commitment technology and the greater flexibility of delegation are not affected. Delegation is still associated with a higher credibility which now, however, comes with a price attached.

26.4 Endogenous choice of bureaucrat's type

If the sovereign can choose the type a of a bureaucrat by a screening mechanism or if complete contracts are available, she would always prefer 'perfect' delegation ($a = 1$). The objective function in (26.6) is strictly increasing in a since an improved match between the sovereign's and bureaucrat's preferences has three beneficial effects. First, it reduces the loss due to the bureaucrat's deviation in the implemented policy if there is no intervention by the sovereign in the second period. Second, costly interventions are less frequent and third, the trade-off between credibility and flexibility is reduced which allows to improve on the time-inconsistency problem.

Chapter 27

Conclusion of Part IV

The solution of time-inconsistency in policy making has received considerable attention in the economic literature. Delegation to an independent agency or bureaucrat has been proposed as a feasible and effective commitment device (Rogoff 1985). However, McCallum (1995) criticized this view by pointing out that independence itself requires commitment on delegation to be effective. One response to this critique was to assume that delegation is for some reason easier to commit on than a specific policy. Another was to combine an independent sources of commitment such as punishment strategies in infinitely repeated games or checks and balances with delegation (Jensen 1997, Moser 1999, Keefer and Stasavage 2003, Driffill and Rotondi 2006). The latter approach has produced mixed results with respect to the additional effect of delegation. Nevertheless, the empirical evidence, especially in monetary policy, finds a strong correlation between delegation and the credibility of policies.

This part contributes to this ongoing debate. Using a setting for which McCallum's '*second fallacy*' holds under complete information, it is shown that introducing uncertainty that creates a trade-off between credibility and flexibility is sufficient to establish a positive relation between delegation and an increased level of commitment as is observed in the real world. This holds even if delegation is costly. However, delegation does not increase credibility *per se* but creates conditions that make investments in commitment more attractive. The key feature is that delegation reduces the trade-off between credibility and flexibility. Incentives to invest in credibility are therefore higher with delegation than without.

There are two basic requirements for this result to hold. First, the sovereign has to have some influence on the degree of the commitment she enters. This is the case for most legislators since they can influence the cost of a future policy change by their choice of the majority rule. Second, the bureaucrat's response to exogenous shocks have to be at least somewhat in line with the sovereign's preferences. This is a straightforward extension of the type selection argument standard in the literature on strategic delegation.

The internal organization of government matters for the credibility of policies. This result is relevant for the implementation of environmental policies discussed in previous parts as well as for a wide range of other policy areas. Hence, the contribution of this final part reaches far beyond the realm of environmental economics.

Chapter 28

Conclusion

28.1 Summary of Results and Policy Implications

28.1.1 Optimal Green Horizontal Innovation

Allowing for new technologies that do not solve the pollution problem once and for all, substantially alters the optimal pollution policy and timing of R&D. In general, a one step search for a backstop no longer represents an appropriate way to model environmental innovation. Research might repeatedly fail to deliver the much wanted backstop raising the question how to manage the increasing number of available polluting technologies and the amount and timing of R&D investment. For the baseline model presented in chapter 3 a number of clear cut results have been established: (a) the optimal R&D sequence is strictly sequential, i.e. at most one technology is developed at any point in time; (b) there is a tight link between the optimal pollution policy and the optimal R&D trajectory since there is a constant threshold pollution stock that triggers new innovations; (c) the optimal pollution portfolio is finite, even if no backstop is developed; (d) contrary to previous results in the literature, the simultaneous use of many technologies is the rule rather than the exception; (e) pollution stocks overshoot, i.e. there are (repeated) periods where stocks are above their long run steady state.

The analysis of green horizontal innovation can inform the political arena on a number of relevant topics. Given a set of technologies, each of which has strings attached, the question might not be to choose the lesser evil and use it exclusively but how to mix them best. The ban of a polluting technology - such as nuclear power in Germany - is likely to be an exaggerated measure unless a viable clean alternative is at hand. The resulting shift to fossil fuels in electricity production contributes to global warming, an environmental problem of comparable size. Moreover, both the stock of nuclear waste and the carbon dioxide concentration might optimally overshoot their long run level.

Technological uncertainty has several effects. While the maximum number of technologies developed is increasing in the probability to develop a backstop, this relation does not hold for the expected size of the portfolio. A greater chance to acquire a clean technology by R&D increases the expected return from investment. Hence, at any given point where no backstop is feasible, research incentives are larger and hence R&D is undertaken more often. For the expected number of available technologies there are two countervailing effects: first, the potential number of innovations is larger, but second the probability to get a backstop and hence stop R&D are also larger. The combination of both results in a non-monotonic, but overall decreasing, relationship between the chance to develop a backstop technology and the expected long run size of the available portfolio. However, the overall pattern of the optimal pollution and research policies remain intact if the beliefs about the feasibility of a backstop are fixed. If they evolve due to learning from the outcome of previous R&D projects, this has effects on the optimal timing of innovations. If updating increases the belief in a backstop, then innovation occurs earlier and more often. The threshold level triggering R&D decreases in the number of past R&D projects technologies. The reverse holds if the belief is decreasing in the number of past 'failures'. However, the maximum portfolio is always finite and, hence, the optimal R&D program is fully determined regardless of the nature of the updating process. This result contrasts the case of varying costs of R&D where potentially infinite sequences of R&D can occur. A case for which no necessary conditions for the optimal timing of innovations have been established yet.

28.1.2 Implementing Policies for Green Horizontal Innovation

Green horizontal innovation poses new challenges to the implementation of the optimal pollution and R&D policies. The following issues are especially important: the simultaneous regulation of different pollutants emitted by the same industry and the creation of research incentives via patents and, at the same time, limiting the distortions caused by monopoly power. Part II establishes a series of results on this matter. In general, both taxes and permits can fail to implement optimal mixes of technologies and optimal research incentives if used exclusively. In contrast to vertical innovations, they achieve static efficiency at least in some cases where patents have been granted for one active technology. However, differentiated pollutants allow for a differentiated regulatory instrument. Using taxes to regulate the established and permits to restrict the use of any new pollutant allows the government to implement the optimal mix of technologies if there are constant returns to scale at the industry level. This result requires that all inputs are in perfectly elastic supply, e.g. due to provision by the world market.

In practice mixes of different instruments are common. The additional flexibility created by such hybrid schemes is both, a curse and a blessing. While an increase in the choice set of the government unambiguously increases static efficiency, the effect on dynamic efficiency is less straightforward. Part III presents a number of cases where research incentives decrease or vanish completely. However, for the implementation of the optimal R&D program with multiple green horizontal innovations presented in part II, flexibility is crucial.

For research incentives to be optimal, the instrument used has to be even more sophisticated. The permits issued for new pollutants have to be sold/auctioned at a reservation price in case research incentives are excessive or pollution has to be subsidized if incentives for R&D are too small. Note that subsidies do not increase emissions neither in the short nor in the long run, since aggregate emissions of the respective pollutant is bound by permits. Hence, in effect, subsidies are a pure transfer to the patent holding firm.

Given that such subsidies are costless and politically feasible, both, the optimal pollution and the optimal R&D trajectory can be implemented without any serious commitment necessary. If, as is likely, public funds are costly, both the optimal amount of subsidization and the credibility of such a policy are changed. Promising to transfer public money to an innovator or, alternatively, not collecting revenue, is no longer credible if the government puts a positive value on public funds. Ex-post the government would like to renege on such a promise and, in the absence of a binding commitment, research firms will not invest in R&D. The ability to credibly commit on the design of future environmental regulation is therefor crucial for the stimulation of environmental R&D - even if intellectual property rights are granted and perfectly enforced. Hence, in practice it is not only important which instrument is used to internalize environmental damages and how stringent future environmental regulation will be, but also auction rules and punishments in case of excessive emissions are important for an optimal policy design.

28.1.3 Commitment and the Internal Organization of Government

The means to achieve governmental commitment are still much debated among economists. Repeated interaction and the internal organization of a government are the two main instruments that are believed to make commitment feasible. Each is based on two separate lines or reasoning: while repeated interaction is necessary to build up reputation and also gives rise to folk theorem type of arguments, the internal organization of government can involve joint responsibility by more than one actor. These can be actors at the same level of hierarchy (multiple veto players) or a sovereign and a subordinate bureaucrat (delegation).

The role of delegation in generating and increasing commitment has been much debated. Part IV contributes some new insights to this discussion. While delegation is unable to improve commitment *per se* and much less to generate it in the first place, it makes commitment more attractive. When uncertainty over future states of the world and, hence, optimal future policies is relevant, there is a trade-off between credibility and flexibility. Delegation allows to relax this trade-off. With delegation credibility depends on the costs to change the institutional structure and, hence, on the (endogenous) decision making costs of the government. On the contrary, flexibility depends on the decision making costs of the bureaucrat. Under discretion both types of cost concerns, credibility and flexibility, are inherently linked since any change of the policy involves the same costs - regardless of the motivation for the adjustment to occur.

Delegation is therefore an effective tool to induce more credibility into policies. This result applies to all areas of policy making and, therefore, is of interest beyond the realm of environmental economics.

28.2 Caveats and Areas of Further Research

It remains to point out that, so far, none of the results has been tested empirically so that they remain hypotheses. Further research should therefore test whether the theory lives up to a broader set of real world observations. Moreover, the models presented are highly stylized. Reducing complexity allows to concentrate on the specific question at hand and allows to solve the problem analytically, deriving explicit solutions. In particular the model in part I is highly stylized. The discussion in chapter 6 shows that relaxing almost any of the assumptions makes analytical solutions hard if not impossible. Partly, numerical methods can be used to enrich the model. However, for other extensions the methodology to address the mathematical complications is yet to be developed. For example, so far, no necessary conditions for optimal control problems with an infinite number of stages have been established. While chapter 5 presents new necessary conditions for the case of technological uncertainty, it is beyond the scope of this thesis to tackle the issue of infinite stages. Hence, there are two avenues for further research. One is to use computerized models to relax some of the assumptions in order to better fit the model to real world applications (e.g. in integrated assessment models used by climate change economists). The other lies in the area of economic theory and aims at an extension of the mathematical toolkit available for dynamic optimization.

With respect to the implementation of policies it is important to keep in mind that the taming of monopoly pricing requires an area of perfectly elastic demand. Effectively addressing market power is feasible only if the returns to scale are constant at the industry level. Hence, inputs have to be in perfectly elastic supply and firms have to be symmetric. Otherwise, a patent holding firm facing a downward sloping demand might find it worthwhile to increase the license fee and thereby reduce output of the protected technology to a suboptimal level. The implementation strategies suggested in parts II and III are nonetheless able to improve efficiency compared to standard tax or permit schemes. However, they might fail to achieve first best. Further exploration of these relations for more general industry structures is desirable.

A major contribution of this thesis is to extend the set of technologies considered in the environmental economics literature. It is analyzed how they affect optimal pollution and R&D policies and how to implement them when technological change is endogenous. Although the incentives to innovate are explicitly modeled one important dimension of research has been treated exogenously: the direction of technological change. An interesting next step would be to use the insights derived in this thesis and use them to enrich available models of directed technological change. It might be particularly interesting to study the different incentives faced by R&D firms in such models. They can choose to invest either in a vertical innovation (reducing private costs or pollution intensity and, therefore, in the spirit of Aghion and Howitt (1992), rendering an existing one obsolete) or in green horizontal innovations that complement existing technologies. A more explicit representation of the R&D sector, including technological leaders and followers, is therefore in order.

Part IV provides a new perspective to the debate on the role of delegation in a government's ability to credibly commit. It reconciles the main two opposing lines of argument. It does so by establishing conditions that allow delegation to be used as a mean to improve the credibility of policies even if both the policy and the institutional structure are subject to the same commitment technology. A question not addressed in this thesis is where this initial commitment comes from. Besides from reputation, the commitment might originate, as suggested, from capacity constraints in parliamentary decision making and flexibility in the choice of the majority rule.

Part V

Appendix

Appendix A

Appendix to Part I

A.1 Proof of Necessary Conditions (5.3) and (5.4)

The first variation of J (see (5.1)) is[1]

$$\begin{aligned}
\delta J &= \left\{H_n\left(t_{n+1}\right)+(1-p)^{n-1}e^{-rt_{n+1}}rR-H_{n+1}\left(t_{n+1}\right)\right\}\delta t_{n+1} \qquad (A.1)\\
&+\left\{\sum_{j=2}^{n}\left[p(1-p)^{j-2}\sum_{i=1}^{j}\mu_i^{Back_j}(t_{n+1})\right]\right.\\
&+(1-p)^{n-1}\sum_{i=1}^{n}\mu_i^{Boom_n}(t_{n+1})\\
&-\left[\sum_{j=2}^{n+1}\left(p(1-p)^{j-2}\sum_{i=1}^{j}\mu_i^{Back_j}(t_{n+1})\right)\right.\\
&\left.\left.+(1-p)^{n}\sum_{i=1}^{n}\mu_i^{Boom_{n+1}}(t_{n+1})\right]\right\}\delta S(t_{n+1}),
\end{aligned}$$

where δt_{n+1} and $\delta S(t_{n+1})$ are perturbations in t^*_{n+1} and $S(t^*_{n+1})^*$. (A.1) simplifies to

$$\begin{aligned}
\delta J &= \left\{H_n\left(t_{n+1}\right)+(1-p)^{n-1}e^{-rt_{n+1}}rR-H_{n+1}\left(t_{n+1}\right)\right\}\delta t_{n+1} \qquad (A.2)\\
&+\left\{(1-p)^{n-1}\sum_{i=1}^{n}\mu_i^{Boom_n}(t_{n+1})\right.\\
&-\left[p(1-p)^{n-1}\sum_{i=1}^{n}\mu_i^{Back_{n+1}}(t_{n+1})\right.\\
&\left.\left.+(1-p)^{n}\sum_{i=1}^{n}\mu_i^{Boom_{n+1}}(t_{n+1})\right]\right\}\delta S(t_{n+1}),
\end{aligned}$$

since no innovation occurs at t_{n+1} in all cases where a backstop has been developed in the past. For these cases, shadow prices are continuous at t_{n+1}. For any admissible

[1] See (Kamien and Schwartz 1993, chp. 13)

permutation δJ must be non-positive at all switching instants $n = 1, ..., N-1$. The first row of (A.2) therefore yields (5.4).

The coefficient of $\delta S(t_{n+1})$ has to be zero and the resulting condition can be simplified to

$$\sum_{i=1}^{n} \mu_i^{Boom_n}(t_{n+1}) = p \sum_{i=1}^{n} \mu_i^{Back_{n+1}}(t_{n+1}) + (1-p) \sum_{i=1}^{n} \mu_i^{Boom_{n+1}}(t_{n+1}). \tag{A.3}$$

Making use of the symmetry assumptions regarding technologies, this yields (5.3).

A.2 Combining the Necessary Conditions: (5.3) and (5.4) to (5.5) and (5.6)

Condition (5.4) requires that $G(t_{n+1}^*) = H_n^*\left(t_{n+1}^*\right) + (1-p)^{n-1} e^{-rt_{n+1}^*} rR - H_{n+1}^*\left(t_{n+1}^*\right)$ is non-negative for all $\delta t_{n+1} < 0$ and non-positive for all $\delta t_{n+1} > 0$. Otherwise, there exist perturbations for which (5.4) becomes positive. $G(t_{n+1}^*) = 0$ is therefore a necessary condition for all $t_{n+1}^* > 0$. For $t_{n+1}^* = 0$, G is allowed to be negative. First consider innovation at some $t_{n+1}^* > 0$, where

$$H_n^*\left(t_{n+1}^*\right) + (1-p)^{n-1} e^{-rt_{n+1}^*} rR = H_{n+1}^*\left(t_{n+1}^*\right), \tag{A.4}$$

is a necessary condition. Substituting (5.2) into (A.4) and simplifing yields

$$\begin{aligned}
e^{-rt_{n+1}^*} \quad & \left[\sum_{i=1}^{n}\left(q_i^{Boom_n^*} - \frac{d}{2} S_i^{*2}\right) + rR\right] + \sum_{i=1}^{n} \mu_i^{Boom_n}\left(\alpha q_i^{Boom_n^*} - \delta S_i^*\right) = \\
& (1-p)\left\{e^{-rt_{n+1}^*} \sum_{i=1}^{n+1}\left(q_i^{Boom_{n+1}^*} - \frac{d}{2}(S_i^{Boom_{n+1}^*})^2\right)\right. \\
& \left. + \sum_{i=1}^{n+1} \mu_i^{Boom_{n+1}}\left(\alpha q_i^{Boom_{n+1}^*} - \delta S_i^{Boom_{n+1}^*}\right)\right\} \\
& + p\left\{e^{-rt_{n+1}^*} \sum_{i=1}^{n+1}\left(q_i^{Back_{n+1}^*} - \frac{d}{2}(S_i^{Back_{n+1}^*})^2\right)\right. \\
& \left. + \sum_{i=1}^{n+1} \mu_i^{Back}\left(\alpha q_i^{Back_{n+1}^*} - \delta S_i^{Back_{n+1}^*}\right)\right\}.
\end{aligned} \tag{A.5}$$

Using $\sum_{i=1}^{n} q_i^{Boom_n^*} = \sum_{i=1}^{n+1} q_i^{Boom_{n+1}^*} = \sum_{i=1}^{n+1} q_i^{Back_{n+1}^*} = 1$, $S_{n+1}^{Boom_{n+1}}(t_{n+1}^*) = S_{n+1}^{Back_{n+1}}(t_{n+1}^*) = 0$ and the optimal pollution policy in case a backstop arrives it reduces to

$$
\begin{aligned}
e^{-rt^*_{n+1}} \quad & \left[1-\sum_{i=1}^{n}\frac{d}{2}S_i^{*2}+rR\right]+\sum_{i=1}^{n}\mu_i^{Boom_n}\left(\alpha q_i^{Boom^*_n}-\delta S_i^*\right)= \\
(1-p) \quad & \left\{e^{-rt^*_{n+1}}\left[1-\sum_{i=1}^{n}\frac{d}{2}(S_i^{Boom^*_{n+1}})^2\right]\right. \\
& \left.+\sum_{i=1}^{n}\mu_i^{Boom_{n+1}}\left(\alpha q_i^{Boom^*_{n+1}}-\delta S_i^{Boom^*_{n+1}}\right)+\alpha\mu_{n+1}^{Boom_{n+1}}q_{n+1}^{Boom^*_{n+1}}\right\} \\
+p \quad & \left\{e^{-rt^*_{n+1}}\left[1-\sum_{i=1}^{n}\frac{d}{2}(S_i^{Back^*_{n+1}})^2\right]\right. \\
& \left.-\sum_{i=1}^{n}\mu_i^{Back_{n+1}}\delta S_i^{Back^*_{n+1}}+\alpha\mu_{n+1}^{Back_{n+1}}\right\}.
\end{aligned}
\tag{A.6}
$$

Using the pollution shadow prices' matching condition (5.3), a straightforward stock matching condition and the absence of a stock constraint for the backstop $\mu_{n+1}^{Back_{n+1}} = 0$, the optimal pollution policy with boomerangs (4.18) and (4.19) and rearranging terms yields

$$
rR=\alpha\left[(1-p)\mu_j^{Boom_{n+1}}-\sum_{i=1}^{n}\mu_i^{Boom_n}q_i^{Boom^*_n}\right]e^{rt^*_{n+1}}. \tag{A.7}
$$

Note that for all optimal pollution policies $\sum_{i=1}^{n}\mu_i^{Boom_n}q_i^{Boom^*_n} = \mu_n^{Boom_n}$. Using (5.3) again, (A.7) simplifies to (5.6).

The proof for $t^*_{n+1} = 0$ works analogously and yields (5.5).

A.3 Shadow Prices When a Backstop Arrives: (5.7)

If a backstop arrives at t^*_{n+1} the stock of all polluting technologies deteriorates according to $S_i^{Back_{n+1}}(t) = S_i^{Boom_n}(t_{n+1})e^{-\delta(t-t_{n+1})}$. Using (4.2) yields

$$
\begin{aligned}
\mu_i^{Back_{n+1}}(t) \quad = \quad & e^{\delta(t-t^*_{n+1})}\cdot\left[\mu_i^{Back_{n+1}}(t^*_{n+1})\right. \\
& \left.+\frac{de^{2\delta t^*_{n+1}}}{r+2\delta}S_i^{Boom_n}(t^*_{n+1})\left(e^{-(r+2\delta)t^*_{n+1}}-e^{-(r+2\delta)t}\right)\right].
\end{aligned}
\tag{A.8}
$$

The transversality condition (4.3) requires that the limit for $t\to\infty$ of the optimal Hamiltonian with the final technology portfolio is zero. Substituting (A.8) and the optimal pollution policy with a backstop technology into (4.3) yields (5.7).

A.4 Proof That Innovation Is Sequential (Proposition 5.2)

In order to prove that innovation is strictly sequential one has to allow for multiple innovations at the same point in time and show that this is not an optimal strategy. If more than one technology is developed at some t_n the optimal pollution policy is a straightforward extension of the one presented in chapter 4. The optimal quantities after during convergence are

$$q_i^{Boom^*}(t) = 0 \quad ,\forall t \in \left[t_n, \hat{t}_n\right], \quad i = 1, ..., n-k, \tag{A.9}$$

$$q_j^{Boom^*}(t) = \frac{1}{k} \quad ,\forall t \in \left[t_n, \hat{t}_n\right], \quad j = n-k+1, ..., n, \tag{A.10}$$

replacing policies (4.18), (4.19), (4.26) and (4.27). The evolution of pollution stocks between innovation and convergence change accordingly. The point in time when stocks have converged is therefore

$$\hat{t}_n = t_n + \frac{1}{\delta} \ln\left[\frac{\delta k}{\alpha} S_i(t_n) + 1\right]. \tag{A.11}$$

If more than one technology is developed ($k > 1$) only the expected shadow prices of new technologies enter condition (5.6). Pollution stocks for both are zero. Reasoning along identical lines as in the proof for Proposition 5.1, one obtains $E\left(\check{\mu}^*_{n+k}\left(t^*_{n+1}\right)\right) = E\left(\check{\mu}^*_{n+k-1}\left(t^*_{n+1}\right)\right)$. Incorporating this into (5.6) yields that research is sequential unless R&D is for free ($R = 0$) or the social planner infinitely patient ($r = 0$). $\square$

A.5 Shadow Price of a New Technology at $t^*_{n+1} > 0$: (5.9)

During convergence following t^*_{n+1}, (4.20) and (4.21) describe the evolution of stocks for technologies n and $n+1$. Using (4.2) one gets the following shadow price dynamics

$$\begin{aligned}
\mu_n^{Boom_{n+1}}(t) &= e^{\delta(t-t^*_{n+1})} \cdot \Big[\mu_n^{Boom_{n+1}}\left(t^*_{n+1}\right) \\
&\quad + dS_n^{Boom^*_n}\left(t^*_{n+1}\right) e^{2\delta t^*_{n+1}} \left(\frac{e^{-(r+2\delta)t^*_{n+1}} - e^{-(r+2\delta)t}}{r+2\delta}\right)\Big]
\end{aligned} \tag{A.12}$$

$$\begin{aligned}
\mu_{n+1}^{Boom_{n+1}}(t) &= e^{\delta(t-t^*_{n+1})} \left[\mu_{n+1}^{Boom_{n+1}}\left(t^*_{n+1}\right) + \frac{\alpha d}{\delta} e^{\delta t^*_{n+1}}\right. \\
&\quad \left. \cdot \left(\frac{e^{-(r+\delta)t^*_{n+1}} - e^{-(r+\delta)t}}{r+\delta} - \frac{e^{-(r+\delta)t^*_{n+1}} - e^{-(r+2\delta)t+\delta t^*_{n+1}}}{r+2\delta}\right)\right].
\end{aligned} \tag{A.13}$$

At $\hat{t}_{n+1}$, stocks and hence the shadow prices of incumbent and new technologies converge. Hence, from $\mu_n^{Boom_{n+1}}\left(\hat{t}^*_{n+1}\right) = \mu_{n+1}^{Boom_{n+1}}\left(\hat{t}^*_{n+1}\right)$ and (A.12), (A.13) and

(4.22) it follows that

$$\begin{aligned}\mu_{n+1}^{Boom_{n+1}}(t_{n+1}^*) &= \mu_n^{Boom_{n+1}}\left(t_{n+1}^*\right) + \frac{d}{r+2\delta}e^{-rt_{n+1}^*} \times \\ &\left[S_n^{Boom_n^*}\left(t_{n+1}^*\right) + \frac{\alpha}{\delta}\right]\left[1 - \left(\frac{\delta}{\alpha}S_n^{Boom_n^*}\left(t_{n+1}^*\right) + 1\right)^{-\frac{r+2\delta}{\delta}}\right] \\ &-\frac{\alpha d}{\delta(r+\delta)}e^{-rt_{n+1}^*}\left[1 - \left(\frac{\delta}{\alpha}S_n^{Boom_n^*}\left(t_{n+1}^*\right) + 1\right)^{-\frac{r+\delta}{\delta}}\right].\end{aligned} \tag{A.14}$$

Further simplifying yields (5.9).

Appendix B

Appendix to Part II

The new technology is used exclusively, if

$$f < c_1 - c_2 + (1 - \alpha)\gamma_1 - \gamma_2.$$

If none of the permit constraints is binding, both permit prices are zero. The threshold level is therefore given by

$$f < c_1 - c_2.$$

If the permit constraint for the new pollutant, i.e. E_2 is binding, the permit price for the first type of permits is $\gamma_1 = 0$ and γ_2 is determined by (11.2). This yields a threshold level (where $\gamma_2 = 0$) of

$$f < P(E_2) - c_2.$$

If the permit constraint for the established pollutant, i.e. $\alpha^{-1}E_1$ is binding, the permit price for the second type of permits is $\gamma_2 = 0$ and γ_1 is determined by (11.2). This yields a threshold level of

$$f < (1 - \alpha)P(\alpha^{-1}E_1) + \alpha c_1 - c_2.$$

Appendix C

Appendix of Part IV

C.1 Proof of Proposition 25.1

For (25.6) to hold $\frac{\partial v}{\partial p}(s)$ and $\frac{\partial \hat{v}}{\partial p}(s)$ have to have opposite signs. This is the case only if $\tilde{p}^*(s) < p^*(s) < \hat{p}^*(s)$. Hence, the implemented policy $p^*(s)$ is strictly between the full commitment and the no commitment policy. This corresponds to a strictly positive but finite c. In this sense commitment is partial.

C.2 Proof of $\mathcal{S}^{Dis}(c_1)$

If $\tilde{p}_2^*$ is not credible because $s < \underline{p}(c_1) - \tilde{p}_1^*$, (26.3) becomes $v\left(\underline{p}(c_1) - s\right) - v\left(\bar{p}(c_1) - s\right) > c_1$ which holds if $s < \underline{s}_1^{Dis}(c_1)$.

If the ex-ante optimal second period policy $\tilde{p}_2^* = \tilde{p}_1^* + s$ is credible (26.3) becomes $v\left(\tilde{p}_1^*\right) - v\left(\bar{p}(c_1) - s\right) > c_1$ which never holds for $s = \bar{p}(c_1) - \tilde{p}_1^*$ which is the largest s for which $\tilde{p}_2^*$ is credible. However, at the lowest s for which $\tilde{p}_2^*$ is credible it holds for some values of c_1. Hence, there is a level $\underline{s}_2^{Dis}(c_1)$ where the sovereign is just indifferent between adjustment and the inherited policy.

However, for all $s > \bar{p}(c_1) - \tilde{p}_1^*$, (26.3) becomes $v\left(\bar{p}(c_1) - s\right) - v\left(\bar{p}(c_1) - s\right) > c_1$ which is zero for all s.

The threshold level $\underline{s}^{Dis}(c_1)$ is thus defined as

$$\underline{s}^{Dis}(c_1) = \begin{cases} \underline{s}_1^{Dis}(c_1) & , \quad s < \underline{p}(c_1) - \tilde{p}_1^*, \\ \underline{s}_2^{Dis}(c_1) & , \quad \underline{p}(c_1) - \tilde{p}_1^* \leq s. \end{cases} \tag{C.1}$$

Hence, the set of s where the sovereign adjusts the policy in the second period is $\mathcal{S}^{Dis}(c_1) = (-\infty, \underline{s}^{Dis}(c_1)[$.

C.3 Proof of $\mathcal{S}^{Del}(c_1, a)$

Five cases have to be considered: a) neither $\tilde{p}_2^* = \tilde{p}_1^* + s$ nor $p^B = \tilde{p}_1^* + as$ are credible because they are smaller than $\underline{p}(c_1)$, b) $p^B = \tilde{p}_1^* + as$ is credible but not $\tilde{p}_2^*$, c) both are credible, d) $\tilde{p}_2^*$ is credible but not $p^B = \tilde{p}_1^* + as$ and e) neither $\tilde{p}_2^* = \tilde{p}_1^* + s$ nor $p^B = \tilde{p}_1^* + as$ are credible because they are larger than $\bar{p}(c_1)$.

a) $s \in (-\infty, \frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}[$
Here, $v\left(\underline{p}(c_1) - s\right) - v\left(\underline{p}(c_1) - s\right) = 0$ hence, (26.4) cannot hold. The sovereign therefore never adjusts if $s < \frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}$.

b) $s \in [\frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}, \underline{p}(c_1) - \tilde{p}_1^*[$
Here, (26.4) becomes $v\left(\underline{p}(c_1) - s\right) - v\left(\tilde{p}_1^* - (1-a)s\right) > c_1$ which does not hold for the lowest s in this set, but holds for some a for the largest admissible s. Hence, there is a $\underline{s}_1^{Del}(c_1, a)$ for which for all admissible $s < \underline{s}_1^{Del}(c_1, a)$ the sovereign adjusts the policy. Note that for some $a > a_1$, $\underline{s}_1^{Del}(c_1, a) > \underline{p}(c_1) - \tilde{p}_1^*$ in which case $\underline{s}_1^{Del}(c_1, a)$ is irrelevant.

c) $s \in [\underline{p}(c_1) - \tilde{p}_1^*, \frac{\bar{p}(c_1) - \tilde{p}_1^*}{a}]$
Here, (26.4) becomes $v\left(\tilde{p}_1^*\right) - v\left(\tilde{p}_1^* - (1-a)s\right) > c_1$ which holds for some $a_1 \leq a \leq a_2$, in the set of admissible s. Hence, there is a $\underline{s}_2^{Del}(c_1, a)$ for which for all admissible $s < \underline{s}_2^{Del}(c_1, a)$ the sovereign adjusts the policy.

d) $s \in]\frac{\bar{p}(c_1) - \tilde{p}_1^*}{a}, \bar{p}(c_1) - \tilde{p}_1^*]$
Here, (26.4) becomes $v\left(\tilde{p}_1^*\right) - v\left(\bar{p}(c_1) - s\right) > c_1$ which holds for some $a_2 < a \leq 1$, in the set of admissible s. Hence, there is a $\underline{s}_3^{Del}(c_1, a)$ for which for all admissible $s < \underline{s}_3^{Del}(c_1, a)$ the sovereign adjusts the policy.

e) $s \in]\bar{p}(c_1) - \tilde{p}_1^*, +\infty)$ Here, $v\left(\bar{p}(c_1) - s\right) - v\left(\bar{p}(c_1) - s\right) = 0$ hence, (26.4) cannot hold. The sovereign therefore never adjusts if $s > \bar{p}(c_1) - \tilde{p}_1^*$.

The threshold level $\underline{s}^{Del}(c_1, a)$ is thus defined as

$$\underline{s}^{Del}(c_1, a) = \begin{cases} \underline{s}_1^{Del}(c_1, a) & , \quad 0 \leq a < a_1, \\ \underline{s}_2^{Del}(c_1, a) & , \quad a_1 \leq a \leq a_2, \\ \underline{s}_3^{Del}(c_1, a) & , \quad a_2 < a \leq 1. \end{cases} \tag{C.2}$$

Hence, the set of s where the sovereign adjusts the policy in the second period is

$\mathcal{S}^{Del}(c_1, a) = \left[\frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}, \underline{s}^{Del}(c_1, a)\right[$.

C.4 Proof of Remark 26.1

For all $a > 0$ it holds that $-\infty < \frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}$. Moreover, $\underline{s}^{Del}(c_1, 1) = \underline{s}^{Dis}(c_1)$ and $\underline{s}^{Del}(c_1, a) < \underline{s}^{Dis}(c_1)$ for all $a < 1$. Hence, $\mathcal{S}^{Del}(c_1, a) \subseteq \mathcal{S}^{Dis}(c_1)$.

C.5 Proof of Proposition 26.2

To proof that $c_1^{Dis} \leq c_1^{Del}$ it is shown that the expected marginal benefit of c_1 is larger under delegation than under discretion, i.e. the term in accolades is larger in (26.8) than in (26.7).

- For $s \in (-\infty, \frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}[$ this holds, since under discretion the marginal increase in adjustment cost shows up and $\frac{\partial v}{\partial p}\frac{\partial p_2}{\partial c_1} \leq 0$ and $\frac{\partial v}{\partial p}\frac{\partial \underline{p}}{\partial c_1} > 0$
- For $s \in [\frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}, \underline{p}(c_1) - \tilde{p}_1^*[$ and $s < \underline{s}^{Del}(c_1, a)$ it holds, since $\frac{\partial v}{\partial p}\frac{\partial \bar{p}}{\partial c_1} < 0 < \frac{\partial v}{\partial p}\frac{\partial p_2}{\partial c_1}$ (Note, $\frac{\partial v}{\partial p} < 0$ and $\frac{\partial p_2}{\partial c_1} \leq 0$ since $\tilde{p}_2^* \leq p_2(c_1)$ in the admissible set of s.)
- For $s \in [\frac{\underline{p}(c_1) - \tilde{p}_1^*}{a}, \underline{p}(c_1) - \tilde{p}_1^*[$ and $s > \underline{s}^{Del}(c_1, a)$ it holds, since $\frac{\partial v}{\partial p}\frac{\partial \bar{p}}{\partial c_1} - 1 < 0 < \frac{\partial v}{\partial p}\frac{\partial p^B}{\partial c_1}$.
- For $s \in [\underline{p}(c_1) - \tilde{p}_1^*, +\infty)$ and $s < \underline{s}^{Del}(c_1, a)$ it holds, since $-1 < \frac{\partial v}{\partial p}\frac{\partial p_2}{\partial c_1} - 1$.
- For $s \in [\underline{p}(c_1) - \tilde{p}_1^*, +\infty)$ and $\underline{s}^{Del}(c_1, a) < s < \underline{s}^{Dis}(c_1)$ it holds, since $-1 < 0 < \frac{\partial v}{\partial p}\frac{\partial p^B}{\partial c_1}$.
- For $s \in [\underline{p}(c_1) - \tilde{p}_1^*, +\infty)$ and $s > \underline{s}^{Dis}(c_1)$ it holds, since $\frac{\partial v}{\partial p}\frac{\partial \bar{p}}{\partial c_1} \leq \frac{\partial v}{\partial p}\frac{\partial p^B}{\partial c_1}$.

C.6 Case with $c_2 > c_1$

If the optimal level of credibility is higher in the second period, than in the first one, the optimal policy level after an adjustment changes to

$$p_2(c_2, s) = \begin{cases} \bar{p}(c_2) & , \quad s > \bar{p}(c_2) - \tilde{p}_1^*, \\ \underline{p}(c_2) & , \quad s < \underline{p}(c_2) - \tilde{p}_1^*, \\ \tilde{p}_2^* & , \quad \text{else.} \end{cases} \tag{C.3}$$

C.6.1 The adjustment decision under discretion

- if $s < \underline{p}(c_2) - \tilde{p}_1^*$ (26.3) becomes $v\left(\underline{p}(c_2) - s\right) - v\left(\bar{p}(c_1) - s\right) > c_2$ which holds if $s < \underline{s}_1^{Dis}(c_1, c_2)$.

- if $\underline{p}(c_2) - \tilde{p}_1^* \leq s \leq \bar{p}(c_2) - \tilde{p}_1^*$ (26.3) becomes $v\left(\tilde{p}_1\right) - v\left(\bar{p}(c_1) - s\right) > c_2$ which holds if $s < \underline{s}_2^{Dis}(c_1, c_2)$.

- if $s > \bar{p}(c_2) - \tilde{p}_1^*$ (26.3) becomes $v\left(\bar{p}(c_2) - s\right) - v\left(\bar{p}(c_1) - s\right) > c_2$ which holds if $s > \bar{s}^{Dis}(c_1, c_2)$.

The threshold level $\underline{s}^{Dis}(c_1, c_2)$ is thus defined as

$$\underline{s}^{Dis}(c_1) = \begin{cases} \underline{s}_1^{Dis}(c_1, c_2) & , \quad s < \underline{p}(c_2) - \tilde{p}_1^*, \\ \underline{s}_2^{Dis}(c_1, c_2) & , \quad \underline{p}(c_2) - \tilde{p}_1^* \leq s. \end{cases} \tag{C.4}$$

Hence, the set of s where the sovereign adjusts the policy in the second period is $\mathcal{S}^{Dis}(c_1, c_2) = (-\infty, \underline{s}^{Dis}(c_1, c_2)[\cup]\bar{s}^{Dis}(c_1, c_2), +\infty)$.

C.6.2 The adjustment decision under delegation

- if $s < \frac{\underline{p}(c_2) - \tilde{p}_1^*}{a}$ (26.3) becomes $v\left(\underline{p}(c_2) - s\right) - v\left(\bar{p}(c_1) - s\right) > c_2$ which holds if $s < \underline{s}_1^{Del}(c_1, c_2, a)$.

- if $\frac{\underline{p}(c_2) - \tilde{p}_1^*}{a} \leq s < \underline{p}(c_2) - \tilde{p}_1^*$ (26.3) becomes $v\left(\underline{p}(c_2) - s\right) - v\left(\tilde{p}_1^* - (1-a)s\right) > c_2$ which holds if $s < \underline{s}_2^{Del}(c_1, c_2, a)$.

- if $\underline{p}(c_2) - \tilde{p}_1^* \leq s \leq \frac{\bar{p}(c_2) - \tilde{p}_1^*}{a}$ (26.3) becomes $v\left(\tilde{p}_1\right) - v\left(\tilde{p}_1^* - (1-a)s\right) > c_2$ which holds if $s < \underline{s}_3^{Del}(c_1, c_2, a)$.

- if $\frac{\bar{p}(c_2) - \tilde{p}_1^*}{a} \leq s \leq \bar{p}(c_2) - \tilde{p}_1^*$ (26.3) becomes $v\left(\tilde{p}_1\right) - v\left(\bar{p}(c_1) - s\right) > c_2$ which holds if $s < \underline{s}_4^{Del}(c_1, c_2, a)$.

- if $s > \bar{p}(c_2) - \tilde{p}_1^*$ (26.3) becomes $v\left(\bar{p}(c_2) - s\right) - v\left(\bar{p}(c_1) - s\right) > c_2$ which holds if $s > \bar{s}^{Del}(c_1, c_2, a)$.

The threshold level $\underline{s}^{Del}(c_1, c_2, a)$ is thus defined as

$$\underline{s}^{Del}(c_1, c_2, a) = \begin{cases} \underline{s}_1^{Del}(c_1, c_2, a) & , \quad s < \frac{\underline{p}(c_2) - \tilde{p}_1^*}{a}, \\ \underline{s}_2^{Del}(c_1, c_2, a) & , \quad \frac{\underline{p}(c_2) - \tilde{p}_1^*}{a} \leq s < \underline{p}(c_2) - \tilde{p}_1^*, \\ \underline{s}_3^{Del}(c_1, c_2, a) & , \quad \underline{p}(c_2) - \tilde{p}_1^* \leq s \leq \frac{\bar{p}(c_2) - \tilde{p}_1^*}{a}, \\ \underline{s}_4^{Del}(c_1, c_2, a) & , \quad \frac{\bar{p}(c_2) - \tilde{p}_1^*}{a} < s \leq \bar{p}(c_2) - \tilde{p}_1^*. \end{cases} \tag{C.5}$$

Hence, the set of s where the sovereign adjusts the policy in the second period is $\mathcal{S}^{Del}(c_1, c_2, a) = (-\infty, \underline{s}^{Del}(c_1, c_2, a)[\cup]\bar{s}^{Del}(c_1, c_2, a), +\infty)$.

C.6.3 Remark 26.1 and Corollary 26.1

Both hold for the case $c_2 > c_1$ as well, since $\underline{s}^{Del}(c_1, c_2, a) \leq \underline{s}^{Dis}(c_1, c_2)$ and $\bar{s}^{Dis}(c_1, c_2) \geq \bar{s}^{Del}(c_1, c_2, a)$.

C.6.4 The optimization problems

The optimization problems corresponding to (26.5) and (26.6) are

$$\begin{aligned} \max_{c_1} \quad & v(\bar{p}(c_1)) - c_1 + r \cdot \left\{ \int_{-\infty}^{\underline{s}^{Dis}(c_1,c_2)} \phi(s) \left[v\left(p_2(c_2, s) - s\right) - c_2 \right] ds \right. \\ & \left. + \int_{\underline{s}^{Dis}(c_1,c_2)}^{\bar{s}^{Dis}(c_1,c_2)} \phi(s) v\left(\bar{p}(c_1) - s\right) ds + \int_{\bar{s}^{Dis}(c_1,c_2)}^{+\infty} \phi(s) \left[v\left(\bar{p}(c_2) - s\right) - c_2 \right] ds \right\}, \end{aligned} \tag{C.6}$$

and

$$\begin{aligned} \max_{c_1} \quad & v(\bar{p}(c_1)) - c_1 + r \cdot \left\{ + \int_{-\infty}^{\underline{s}^{Del}(c_1,c_2,a)} \phi(s) \left[v\left(p_2(c_2, s) - s\right) - c_2 \right] ds \right. \\ & \left. + \int_{\underline{s}^{Del}(c_1,c_2,a)}^{\bar{s}^{Del}(c_1,c_2,a)} \phi(s) v\left(p^B(c_1, a) - s\right) ds + \int_{\underline{s}^{Del}(c_1,c_2,a)}^{+\infty} \phi(s) \left[v\left(p_2(c_1, c_2, s) - s\right) - c_2 \right] ds \right\}, \end{aligned} \tag{C.7}$$

respectively.

The first order conditions are

$$\frac{\partial v}{\partial p} \frac{\partial \bar{p}}{\partial c_1} - 1 + r \cdot \int_{\underline{s}^{Dis}(c_1,c_2)}^{\bar{s}^{Dis}(c_1,c_2)} \phi(s) \frac{\partial v}{\partial p} \frac{\partial \bar{p}}{\partial c_1} ds = 0 \tag{C.8}$$

and

$$\frac{\partial v}{\partial p} \frac{\partial \bar{p}}{\partial c_1} - 1 + r \cdot \int_{\underline{s}^{Del}(c_1,c_2,a)}^{\bar{s}^{Del}(c_1,c_2,a)} \phi(s) \frac{\partial v}{\partial p} \frac{\partial p^B}{\partial c_1} ds = 0.$$

Again, the marginal gain from commitment is larger under delegation than under discretion since Remark 26.1 holds and $\frac{\partial v}{\partial p} \frac{\partial \bar{p}}{\partial c_1} \leq \frac{\partial v}{\partial p} \frac{\partial p^B}{\partial c_1}$ for all admissible s. Proposition 26.2 therefore holds for the case $c_2 > c_1$.

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