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ECONOMIC FRAMEWORKS FOR THINKING ABOUT GROWTH, SUSTAINABILITY, AND THE ROLE OF STATE INTERVENTION:

PATHS TO GREEN ECONOMIES

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Economic Frameworks for Thinking about Growth, Sustainability, and the Role of State Intervention: Paths to Green Economies*

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Abstract

The economic growth literature is surveyed in regard to the question of sustainability and innovation. It is argued that the state is able to elect the technologies on which its economy is based, and that these technologies (and the capital in which they are embedded) are the fundamental determinants of the mix of environmental and consumption goods and services produced in that economy. The basic mechanism for inducing a particular technology choice is the use of "resource management": the introduction of any mechanism that provides a signal of increased future resource scarcity. The response of the economy to such a mechanism is to invest in the technologies and the capital goods that embody that future price path. This implies that a state should introduce resource management for the purpose of electing its future development path, moreso than to clean up after past development. This dynamic approach to regulation is associated with the so-called "Porter hypothesis", and emphasises that the dynamic and long term consequences of resource management are far more important than the static and short term ones. It is clear from the economic literature on innovation policy that state intervention is critical to optimal innovation, although the most fundamental form of innovation remains resource management (increased shadow prices). The timing of such interventions is a matter of fairness within the society concerned, but also a matter of competitiveness. The order of adoption of technology is important in determining the total benefits that a state can receive from its adoption. States that lead in terms of environmental and innovation policy can often be the most significant beneficiaries from the adoption of environmental management.

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1 Introduction

The "Greening of Economies" is currently a topical issue regarding development, especially in these times in which the world is assessing the impact of the Rio agenda and the various agreements on environment and development. The shifting of the world's economies onto paths that are consonant with the globe's resource base is an important objective, and one that warrants serious and lasting consideration. To achieve this objective, it is important to consider both how individual economies can pursue more sustainable growth paths, and how more sustainable growth paths may be devised and delivered for their consideration. In this paper we set out what economics has to say on some of the topics most closely related to the issues of environment, development and the issues relating to sustainable development paths.

The economic analysis of the question of sustainability grew out of the 1970s commodities crises, and continued into the examination of global resource concerns such as climate change. It continues to function as a field of analysis focused on the issues of technological change, innovation, and investment in new development paths. The enquiry in this area concerns the role of resource scarcity in driving development in the direction of sustainability. To what extent do markets and prices help to guide an economy away from resource-based constraints, and in the direction of future growth?

A separate area of economic analysis focused on the creation of new options in the face of real constraints concerns the questions of growth and innovation. Many problems that societies need to resolve require some sort of incentive mechanism in order to secure investment in their resolution. The nature of these questions and the mechanism design required for their resolution are questions at the core of the fields of endogenous growth, information and innovation.

Finally, there is an important issue concerning the distribution of the benefits from sustainable development paths. It is clear that, in the first instance, it is as much a matter of fairness as benefit that warrants the pursuit of these new paths and technologies. Nevertheless, the distribution of benefits from the adoption of new technologies is heavily skewed towards the innovators and early adopters of these technologies. A final question for consideration is the pursuit of international competitiveness, and the rules of the game that will enable benefits to be distributed fairly from this important competition.

These are the economic issues we consider to be within the question of "greening the economy". In this paper we set forth the basic economics of growth and sustainability, then look at how states intervene to place societies on a given development pathway. We then consider how resource management is critical to the implementation of a given pathway's sustainability, and how this election determines the mix of goods and services a society receives across time. We examine the socially optimal form and level of state intervention in the economy to attain a given pathway. Then we turn to the competitiveness of this choice - the way in which the choice made determines the distribution of benefits as well as the achievement of the development path. In sum, the review attempts to demonstrate the important questions relating to the problem of electing pathways to green economies, and indicates how states should frame their consideration of this important issue.

2 An Overview of Growth Theory: the Relationship between Growth, Natural Resources and Technological Change

2.1 Growth Theory with Resources – General Requirements for Sustainability

The vision of a "Green Economy" implies the pursuit of economic development along a path of sustainable growth. In this section, we review growth theory and its relationship to natural resources and technological change. We discuss what conditions are required for the exploitation of resources along a path of sustainable growth.

The problem of finiteness, together with the question of whether growth can be sustained in face of resource limits, featured at the centre of many of the earliest economic works. Both Malthus and Ricardo believed that growth could not be sustained beyond a certain limit. In modern times, a similar argument based on population growth, diminishing returns to labor and fixed supply of land was made by the Club of Rome in its publication "The Limits to Growth". Meadows et al. [1972] produced simulations based on a growing world population within a framework of finite resources, and demonstrated that human society would eventually run out of resources and growth would cease.

The work of Meadows et al. [1972] raised the question of sustainability in the modern era, although it did so in a highly simplified fashion. The limitations of the approach related to its simple linear models of economic development and resource depletion. These models did not provide for any feedback within the economy, or any technological response to increasing scarcities. Economists pointed out that the history of the industrialisation of the US and other western economies did not demonstrate the sort of simple path toward decreasing returns that these models implied [Smith, 1979]. In fact, the history of resource depletion in countries such as the US demonstrated that productivity did not decline in the face of resource scarcity, on account of substantial amounts of technological change in the industries concerned.

This experience pointed to the importance of two factors in avoiding the pessimistic outcomes of the "Limits to Growth" literature.

1. a structure of production flexible enough to allow for substitution between limited and abundant inputs as well as different forms of capital ("substitutibility in production"); and
2. a form of technological change that was effective at improving productivity in the face of declining resource throughputs ("resource augmenting technological change").

Together these two points constitute an argument that the limits to growth may be avoided if technological change of a given type occurs, and if natural resources are capable of being substituted for by other economic resources. In the remainder of this section we outline how this argument was developed, and the fundamental importance of these two conditions.

Substitutability within the Production System

With regard to substitution, Solow has argued that it is possible to conceive of natural resources as the "natural form of capital". That is, stocks of natural resources are the initial capital account, from which all flows of goods and services derive in the initial stages of development. One of the things that occurs with increasing development is the conversion of some amount of the natural form of capital to other (physical or human-made) forms of capital. Then, human society possesses several forms of capital: natural capital, physical capital and human capital. Societies convert one form of capital to another form of capital in order to achieve a more productive economy [Solow, 1974] It is this rebalancing of the capital portfolio that is one of the primary drivers of development. In this conception of natural resource depletion as conversion, it is to be expected that the reduced reliance upon a natural resource economy will be combined with general increases in economic welfare. The capacity for this process to continue indefinitely depends entirely upon the limits on the extent to which physical capital is able to substitute for natural capital.

This assumption of the malleability of the production system results in a very simple rule for sustainability. Complementary to the arguments of Pezzey [1992] and Dasgupta and Heal [1980], Hartwick [1977] and Solow [1974] add the *Hartick-Solow rule for sustainable development* . The Hartwick-Solow rule provides that one should "invest all profits or rents from exhaustible resources in reproducible capital"[Hartwick, 1977, p. 972]. Following this rule can in theory generate a constant stream of consumption. Once again, this is a rule for sustainability that is derived from the single belief that it is the amount, and not the form, of the capital account that matters. It is based on the assumption of perfect substitutibility.

Form of Technological Change

Even if natural and man-made capital are perfect substitutes, the limits to growth scenario still results from the single assumption of decreasing returns to capital [Smulders, 2000]. In the absence of any technological progress, additional units of capital would yield a decreasing marginal product (under this assumption). Growth is driven by capital accumulation and the growth rate continuously declines and eventually reaches zero.

Nordhaus et al. [1992, p. 16] argues that technological progress can overcome resource constraints and diminishing returns under some conditions. Natural resource economists usually assume that the increasing scarcity of a resource results in incentives to search for new technologies ("backstop technologies") that will rely upon less scarce inputs [Dasgupta and Heal, 1980]. Therefore, investments in technological change must occur in order to compensate for increasing scarcity, and they must take the precise form of moving the economy toward techniques less reliant upon natural resources that are increasingly scarce; the technological change must be "resource-augmenting" to an extent sufficient to compensate for the declining prevalence of resources in the economy.

Dasgupta and Heal [1974] point to the importance of the elasticity of substitution between reproducible and exhaustible resources. The optimal depletion of a resource depends on whether the resource is essential to production (i.e. either the resource is a necessary input for the production of a final good so that the marginal product of the resource is unbounded). The important point here is that the extent to which a resource is "essential" may change over time. Capital stocks are built to rely upon specific forms of resources, and these forms of capital may change as the scarcity of the resource changes. As resource scarcity increases (and so long as prices reflect this scarcity), it is important that capital stocks adapt to the prevailing market conditions and rely only upon inputs that are most economical. Hence, technological change must take the specific form of enabling the economy to continually shift toward increasing reliance upon less scarce resources.

Summary: sustainability in the face of increasing natural resource scarcity:

How can a process of development be sustained in the face of declining natural resource throughput? (We define sustainability following Pezzey [1992] as non-decreasing utility over time.) [1]

First, it will be important to achieve some manner of resource-augmenting technological process. For example, Pezzey [1992] demonstrates in a simple model of cake-eating that for sustainability to hold the rate of technological progress must be greater than the utility rate of discount. This means that society must value the future sufficiently to provide technological progress at an adequate rate to compensate for its consumption.

And, furthermore, the form of technical progress must be of a form that allows society to substitute away from reliance upon those forms of natural resources that are becoming increasingly scarce. Finally, it is necessary that the value received from extracting resources must be reinvested in other forms of capital. In sum, society must investment in capital and technology for sustainability to occur, and that investment must be of a quantum to replace depleted natural resource stocks, and of a form that will enable production to continue in a world of increased scarcity.

We may view these questions of sustainability in the more concrete world of the mining of an exhaustible resource. Hotelling analyzed this question first in the context of "the mine owner": a metaphor for a situation in which the entire amount of resource available is limited and managed. The question then is: How would market forces determine the way in which society (the mine owner) would deplete this asset? In particular, what forces might prevent the mine owner from depleting the entire stock at once.

These are also known in economics as "cake-eating models", and consider the reasons that one generation of owners will leave anything useful for the next. What incentives are there to stop the current owners from eating the entire cake? In this framework, the market generates incentives for the mine owner to exploit the natural resource to the extent that the natural resource and alternative forms of investment in capital yield the same return. If keeping the natural resource untouched would generate higher profits in present value terms, no exploitation would occur. Conversely, if other forms of capital would yield a higher return, the optimal choice of the mine owner might be to extract the entirety of the natural resource and to invest it in the higher yielding asset [Krautkraemer, 1998]. The equalization of yields across natural and physical capital implies that the perceived price of the natural resource must increase at the rate of interest - the marginal rate return available on all societal assets. This constitutes the simplest version of the "Hotelling rule": market forces will in themselves cause a society to allow the resources to be released continuously onto the market (rather than consumed all at once) - resulting in continually declining throughput at continually rising prices.

Within this paradigm, it is possible for a society to achieve sustainability in a world of declining throughput. The path is described as follows: Natural resources are relatively abundant in earlier periods of development. As the resource is exploited, its price increases and the quantity available to be exploited across time continues to decline The society then continues to mine the resource at a declining rate, but yielding a higher value in each time period. Figure 1 sets out this sort of "Hotelling rule" path of extraction for an exhaustible resource, demonstrating how declining throughput is compensated for by increasing prices for the available resource. It

[1] Krautkraemer [1998] provides an in-depth review regarding the progress of economic theory and empirical analysis regarding this question.

is the re-investment of the funds from the mined resources, into specific forms of capital stock attuned to increasing natural resource scarcity, that generates an economy capable of producing constant outputs against a background of continually declining throughputs.

The conditions for sustainability then may be stated something as follows:

1. the society will commence with heavy reliance upon and use of the natural resource base (high throughput) and will continue across time to use less and less at an increasing price (Hotelling's Rule);
2. as the society mines that resource base, the society must invest the received value from that resource into other forms of capital (Hartwick-Solow Rule);
3. as the resource becomes more scarce, the society must ensure that existing markets and institutions register that increasing scarcity (incentive mechanism condition - see section 2.2);
4. as the price of the resource increases, the society must invest in producing a type of technological change that enables the newly created capital stock to generate output with reduced resources (technical change condition).

This description of the resource-based development path indicates that societies have a choice (at each point in time) of the resources, technologies and capital stocks on which they depend. Sustainable investment at any point in time is dependent on seeing the "correct" path of the resource price into the future, indicating the path of real scarcity of the resource. If this is perceived correctly, then sustainable investment accords with creating the technologies and the (technology-embedded) capital stocks that anticipate and incorporate the real scarcity of natural resources. The key to sustainable growth is adequate investment at each point in time that embeds the real future scarcity of resources into the current choice of technology and capital stock.

2.2 Growth Theory with Technology: The Importance of Incentive Mechanisms in Growth

Economists have increasingly built the choice of technology into the growth framework. Neoclassical growth theory recognized technology as a primary driver of growth - through the mechanism of saved consumption and investment. In the next conceptual step, technological progress was no longer assumed to occur exogenously but was recognised to be the result of investment in research and development (R&D) activities. It is this investment in technologies - both their level and their direction - which determines the growth pathway for an economy. In addition, governments are important motivators of the direction and level of R&D, and through this influence shape technological change and influence the growth trajectory of the economy.

It is generally recognised that much important technological change requires government intervention. Innovations are associated with positive externalities in society. New innovations are usually seen to be coming from the existing body of knowledge. Furthermore, innovations also may have other positive effects which are not captured in the private benefits to the innovator [Arrow, 1962]. Consequently, the level of investments in R&D is usually seen to be lower than optimal. Governments can remedy underinvestment by creating incentive mechanisms for

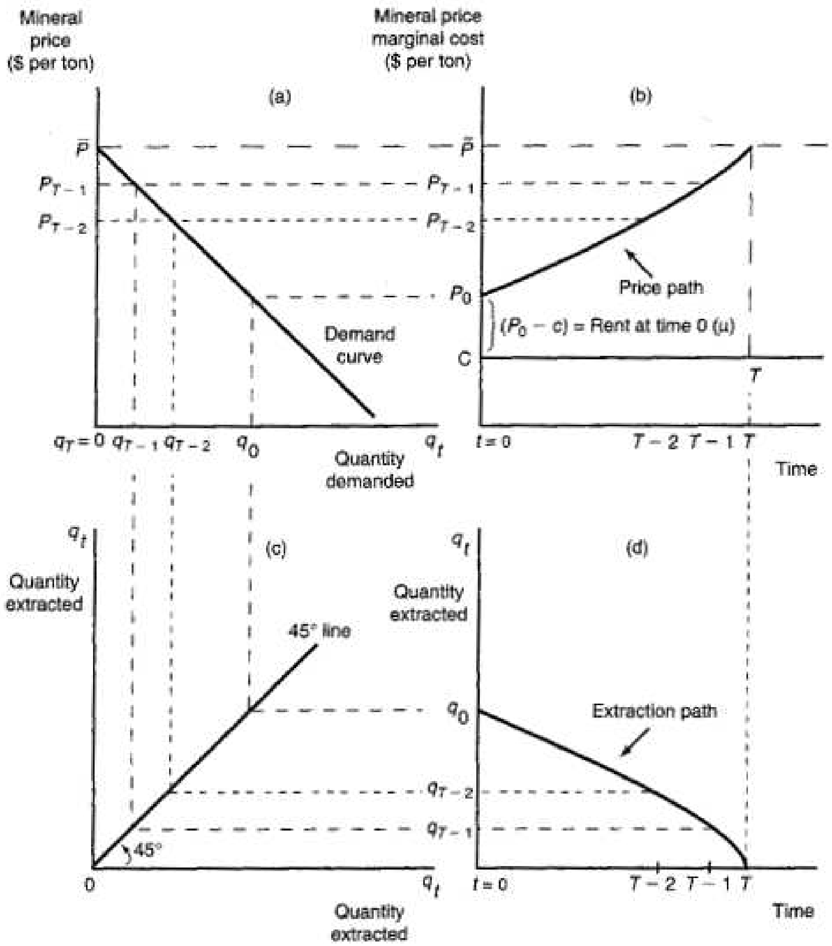

Figure 1: Nonrenewable Resource Use, source: Hartwick and Olewiler [1997, p. 282].

investment or by directly subsidizing or pursuing research. In section 7.4, we discuss further appropriate polices to enhance research.

In natural resource economics, it was always assumed that it was cost-savings that would drive the investments in innovation, and the resulting direction of technological change. As described in section 2.1, perceived increasing resource scarcity implied a path of increasing prices, and these increasing prices created the incentive to invest in technologies that relied on other inputs. The creation of a new technology that shifted the economy away from reliance upon increasingly scarce resources avoided the path of increasing expenditures. The present value of these avoided costs generated the incentives to invest in the technologies that would do so [Dasgupta and Heal, 1980]. We will see in the next section that "management" is the term used in resource economics to describe the creation of the increasing price pathway that will result in the incentives to innovate.

Endogenous growth theory (Romer [1986, 1990], Aghion and Howitt [Aghion et al., 1998]) generalised this concept. This advance in growth theory is based on the idea that technological progress is not an exogenous process but rather a consequence of investment in research more generally. In Romer's approach to growth theory, technological progress or innovation is driven by new ideas which generate rents to the inventor. Ideas or innovations are produced by a research sector and the result of investments into research and development (R&D)- in the pursuit of innovation rents. Romer's approach focuses on the importance of investments in R&D as the mechanism driving the level and direction of technological change. These investments may be made directly by the government, or induced by use of any sort of incentive mechanism. In contrast, Aghion and Howitt take a Schumpeterian approach to endogenous growth, and focus their approach on the use of incentive mechanisms to drive firm-level investments in R&D. Firms conduct research in their self-interest in order to compete in the market. If the investment in R&D turns out to be successful, the firm can appropriate a monopoly rent from the innovation, until its innovation is superceded. In this case the government's role is the creation of mechanisms that enable the appropriation of innovation rents. In either scenario, it is the pursuit of "innovation rents" that generates investment in innovation, and investment that generates new technologies.

Growth theory explicitly recognises that investment into innovation is responsive to many different forms of incentive mechanisms. That mechanism may take the form of direct subsidies, patents/prizes, or even avoided taxes. The analytical framework is identical to that used in natural resource economics: the direction and extent of technological change is driven by incentive mechanisms that enable the appropriation of innovation rents.

Most importantly, the endogenous growth literature explicitly recognises the role of the state in providing the incentives to innovation. It is the function of the state to create the mechanisms that enable the innovator to capture of the value of innovation, and this is a fundamental approach to the furtherance of growth and development [Foray, 2009]. Therefore, the second important part of choosing a development path is the component of government intervention. Since the choice of a development path hinges upon the selection of the technological and capital base that will drive it, it is critical that these choices are properly motivated. The literature on technology and growth makes clear that the state plays a crucial role in determining the correct incentives for optimal investments in base R&D and innovation. These investments may take many forms (subsidies to R&D, cost savings from tax or permit avoidance, prizes and patents) but the crucial point is that state intervention is a critical component for determining the development path, irrespective of the incentive mechanism relied upon.

2.3 Conclusion - Theory of Growth and the Green Economy

The opening chapter of the paper has set out how growth theory has incorporated into its analytic framework the importance of resource scarcity and technological change. Economics assumes that resource scarcity is increasing across time, but that the expectation of increased scarcity provides incentives for technological change. For sustainable development to occur, a form of technological change must occur that correctly anticipates the path of resource scarcity (indicated by the resource constraint's "shadow price" - i.e. the value of the resource indicated by its relative scarcity). Society must invest in a new capital stock - to replace the resources being depleted - and that capital stock must be of a nature that anticipates impending resource scarcities. In the economic framework, it is possible for all of these things to occur in response to the rising price path inherent in increasing resource scarcity.

On the other hand, the theory of endogenous growth and the field of technology policy makes clear that the attainment of specific objectives regarding innovation is an important function of government. Innovation depends upon the entire stock of knowledge and research and development in society, and so general incentives to invest are important to determine the general level of investment. More importantly, the specific direction of technological change is determined by incentive mechanisms that render information generation appropriable. Without such mechanisms, there can be little prospect for substantial targeted investments in innovation.

Therefore this quick survey of economic theory, as it applies to resource scarcity, indicates that the key element of sustainable growth is the targeting of the optimal level and form of technological change. Within resource economics, such technological change can be driven by increasing future price paths. Within growth theory, the emphasis is on government intervention and investment in innovation and knowledge. Both market mechanisms and government interventions are important for engendering the changes necessary to address ultimate scarcities.

In the remainder of the paper we turn to considering some subsidiary issues relating to these problems of sustainability, and the role of governmental intervention. We look at how governments intervene within the paradigm of resource economics, by electing the scarcity value (the "shadow value") the society assesses to a resource. In this way, a government is able to drive an economy toward or away from reliance upon particular resources. We also look at the way that governments can intervene in order to drive innovation and technological change. Finally, we look at the reasons that governments would choose to intervene in economies - for reasons of either social welfare or competitiveness.

We proceed as follows: First, we set out the standard approach to implementing a development path and the empirical literature that documents the standard approach in regard to different jurisdictions and different environmental services (section 3). Then we present an alternative approach to a development pathway – one based on increased intervention for purposes of enhancing the rate, and directing the path, of technological change.

The argument is over whether it is possible for such enhanced technological progress to benefit the economy more generally, enhancing R&D, innovation and growth - the so-called Porter hypothesis (section 4). In section 5, we discuss the basic issue this raises – the question of the optimal rate of technological change and innovation generally – a question of optimal innovation policy. Then we turn to the competitiveness aspects of innovation and growth – can states benefit from enhanced intervention and innovation relative to other states? What are the characteristics of an economy that will determine whether such intervention will be beneficial or not? (sections 6-9).

3 Growth, Pollution and Institutions: The Choice of Pathway

3.1 Management: Choosing Institutions to Implement Specific Pathways

The election of any given development path will depend upon the choice made by the government concerned. Markets generate signals of resource scarcity, but the final shadow value internalised within the economy is a decision for the government. Governments may choose to intervene to re-set shadow values - on account of the presence of externalities or missing markets or simply because a different mix of goods and services is desired. If the government intervenes in order to shift the economy onto a different pathway of resource depletion, it usually does so via a process that is termed "management". Management is the term of art we will use to describe any process by which the government restricts access to a resource (by means of taxes, standards, quotas or other restrictions) and thereby increasing the perceived scarcity or shadow value of the resource.

We will examine a model by Nancy Stokey to give an example of how a government's decision to implement management will thereby determine a chosen pathway of resource use, thus determining the forms of goods and services produced within that economy. Stokey [1998] examines society's choice of optimal path, as a decision by each society on the mix of outputs that are desired from its production system. Stokey defines a social welfare function in which the society values both environmental services and economic goods and services, and social choice comes down to the election of the precise mix of environmental vs. economic services produced at each point in time. It is the election of this development path that lies at the base of her model.

Then her model provides that the chosen path of growth and production results from the management system put into place with regard to the production system. When society elects a management system (z) under which it restricts access to resources, the economy shifts to the production of greater levels of environmental services and lower levels of production goods. Low levels of management result in levels of pollution, but with little cost of management (in terms of foregone production). Therefore, society can choose between higher productivity and lower pollution levels at each point in time. Since welfare is based on both environmental and consumption goods, society desires a balance of consumption goods and environmental goods. When society has few consumption goods (low development), it is optimal to employ the highly productive and polluting management system. As production continues, the accumulation of both stocks of pollution (X) and stocks of consumption goods (y) results in an increasing relative weight being placed on environmental preferences. In order to re-balance the objective function, the state invests in management (reduction in z), and thus shifts the balance towards the production of environmental services in mixed production. At each point in time thereafter, states may elect their path of mixed production (relative balance of growth and environment) by implementing these preferences through increased investment in management (and hence reduced levels of emissions per unit of output –z).

Therefore the Stokey model provides a description of a typical development path for a society commencing from a very low level of development. The model demonstrates how such a society can move from a natural capital based society (with large flows of environmental goods and services) toward a physical capital based society (with consumption goods) through the allowance of unmanaged production. As such a pathway is pursued, the stock of natural capital declines and the stock of consumption goods increases, until the point when the society would elect to slow the process of depletion. This change is occasioned by the implementation of "management" - the means by which the state slows the rate of environmental decline and implements a chosen balance in the production of environmental and consumption goods.

The figure below - from Stokey (1998) - demonstrates how such a newly developing society increases its accumulation of pollution (x) and production (y) from the outset, by allowing markets alone to determine access to particular resources (and thus to set shadow values). When the society perceives that resource scarcity has reached its limit (in terms of the accumulation of pollution), then the society introduces management to re-set the shadow value of those resources and thus place the economy onto a different development path. In this way, governments are able to intervene in order to take control over the vector of goods and services (environmental and production-based) that the economy produces.

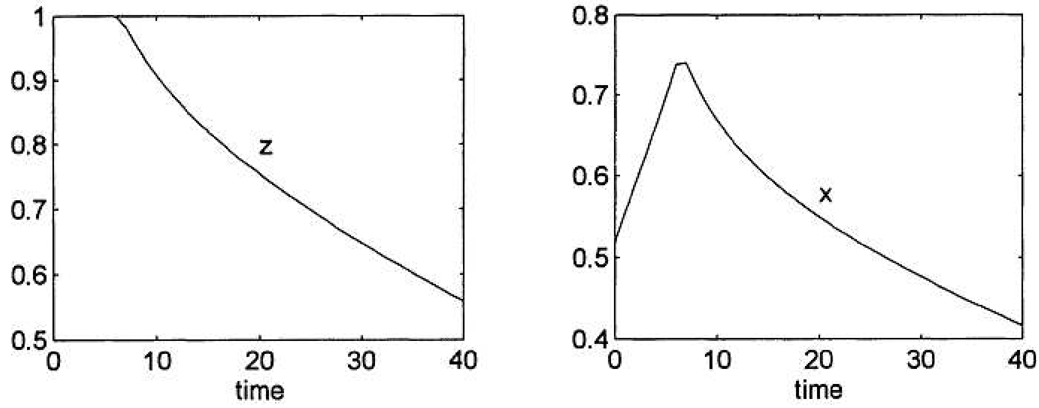

Figure 2: Choice of management and mix of production, source: Stokey [1998].

The same point is made by other authors. Smulders et al. [2005] models the transition from dirty to clean technologies within a Schumpeterian endogenous growth framework. In this framework he demonstrates a very similar story to Stokey's. Initially, only a non-polluting general purpose technology is available and no pollution is emitted. Pollution arises as firms adopt a newly available low cost (labor saving) but dirty technology. Then, firms invest further in the lower cost technology, and pollution rises further with rising output. In this phase, the society has not yet perceived pollution as a "bad" and the sole objective of the economy is the production of economic goods and services not environmental. When society becomes aware of the pollution problem, it enters into an interventionist phase and the government introduces management by levying an emission tax. Production of the polluting goods becomes less attractive, hence, pollution falls to a lower and constant level. Investments are then shifted towards R&D for reduced pollution rather than reduced labour costs. The general purpose technology resulting from this investment is cost reducing in the sense that it reduces emissions and firms save pollution tax expenditures. Thereafter, the economy enters a clean-up phase and pollution further declines.

Here the management mechanism used by the state is a tax that incorporates the true resource-scarcity inherent in the production of the polluting good. The new technology incorporates the information on the environmental costs, transmitted through the emissions tax. And then the economy is placed on a new path - of R&D, investment, production, and consumption - consonant with the newly introduced resource shadow value?

Why is it important for states to intervene to set their own "shadow values" for important resources? If a resource price does not reflect true scarcities, then the market price may be leading the economy down a dead end. This could be the case for fossil fuels, for example, if the resource price path does not incorporate the climate change impacts implicit in their use. Then the imposition of a "carbon tax" is an important management mechanism for the purpose of shifting innovation and investment into capital stocks that correctly anticipate climate impacts within the economic system. Without the management mechanism, the system of investment and innovation is being directed toward the wrong (i.e. unsustainable) path.

By setting up institutions and policies which internalize the environmental costs of economic growth, the government establishes the incentives to develop technologies which incorporate the information on the environmental externality and the future price path of the resource. Given the long-lasting nature of capital which incorporates the technological state of the art at the time of investment, it is important to that investments are forward-looking (incorporating the correct resource scarcity into the future). "Management" is the term of art used to describe the process by which states determine the direction and level of investment onto a sustainable development path.

3.2 Pollution and Growth: Trade-Offs, Social Welfare and Institutional Choice

We have examined the idea that states can elect the development path they follow - choosing the mix of environmental and consumption goods produced at each point in time. It has been argued that states automatically deplete natural resources, and rebalance their economies away from exclusive reliance upon natural capital, as they initially develop larger production sectors, but that the introduction of "management institutions" then accomplishes the purpose of halting this process of resource decline. Management may then be used to determine the precise capital base on which the society relies.

In this section, we wish to examine the empirical evidence of the relationship between growth and environment, in order to ascertain whether this sort of development path has been observed in practice. Do states practice management in the manner we have set out above, i.e. where they intervene to arrest the decline of resources? (e.g. In this section, we will give an overview of the academic discussion and empirical evidence on the relation between pollution and income.

Grossman and Krueger [1993] first noted that the relationship between pollutants and economic development was similar to the income-development curve remarked upon by Kuznets. Subsequently, a large literature developed examining this empirical relationship - under the term "Environmental Kuznet Curve (EKC)". In general, the literature has found substantial but not conclusive evidence across time and across countries that resource scarcity declines at later stages of development.

For some pollutants, empirical evidence supporting the EKC hypothesis can be found in the literature. Grossman and Krueger [1995] find an inverse-U shaped curve examining four indicators (urban air pollution, oxygen in river basins, fecal contamination of river basins and heavy metals). Jänicke et al. [1989] find that the strong correlation between economic performance and environ-mental pollution, unequivocal in 1970, had become much weaker in the 1980s and that a "delinking of economic growth from material intensive industrial production processes is particularly evident".

However, there is no consensus regarding this question in the literature. Some authors also provide evidence which is in contradiction with the EKC hypothesis. For instance, Hettige et al. [2000] measure the effect of income growth on three determinants of pollution and eventually reject the EKC hypothesis regarding industrial water pollution. He finds that instead of rising and then falling pollution levels, the level of pollution remains constant after an initial increase. Harbaugh et al. [2002] perform various robustness and specification tests and find that EKC is sensitive to those changes.

Economic theorists have proved capable of reproducing the inverted-U shape based on different economic reasons. The previously discussed models by Stokey [1998] and Smulders et al. [2005] generate this feature as a result of government intervention – which is the most prominent explanation of the Kuznet curve in the literature [Dasgupta et al., 2002]. In the former model, it is optimal to use highly productive but polluting technologies at lower levels of income. After a certain threshold, the government optimally intervenes and drives back pollution. In the later model, society is not aware of the hazardousness of pollution. When it realizes the problem, it demands for pollution control which enhance technological innovation eventually driving back pollution levels.

Management institutions usually operate in these models through the mechanism of induced technological change. In Andreoni and Levinson [2001]'s model the EKC results from technological features (increasing returns to scale in abatement technology). In their review, Dasgupta et al. [2002] identify other possible explanations. Economic liberalization can also contribute to a inverse-U shaped relation through composition effects, scale effects and the availability of better technology. Moreover, Dasgupta et al. [2002] point to the importance of pressure from market agents, better regulation, pervasive informal regulation and better information.

There is mixed empirical evidence on the existence of the EKC; for some pollutants such a relation may exist and in other cases it is much less obvious. But this is simply indicative of the fact the movement onto a path of improved environmental performance (with growth) is not automatic. It occurs through government intervention, induced technological progress and consequent alteration in the mix of goods produced within the economy.

3.3 Conclusion – the Static Impact of Implementing Environmental Preferences

States can choose the balance of different forms of goods and services, and do so by means of intervention within the economy. With regard to the balance between environmental and consumption goods and services, the intervention is usually termed "management", which raises the scarcity value of certain natural resources (through taxes, permits, or increased regulatory restrictions) and rebalances the economy away from their exploitation and conversion (thus preserving greater flows of services from these resources at the expense of lost consumption goods and services). This is the basic static view of state intervention and the choice of development path. In this view, there is a fundamental trade-off existing between the growth in consumption and the loss of environmental resources; maximum growth is pursued by reason of lack of management and the introduction of management comes at the cost of reduced growth. As development progresses, management institutions are introduced (in this view) in order to shift the balance of production toward an increased proportion of environmental goods and services.

4 State Intervention, Induced Innovation, and Growth: the Porter Hypothesis

In the previous section we presented the literature on how states can intervene to elect the development path for their economies. The objective of states - in those models - is simply to determine a different mix of goods and services produced within the economy. At early levels of development, the states in these models do not intervene within the economy, and the economy focuses solely on the production of market-based goods and services. At later stages of development, state intervention is capable of generating a broader mix of goods and services, both environmental and market. Government intervention in this model is simply for the purpose of determining the vector of goods and services being produced.

The problem with this static view of government intervention is that it elides the question of the impact of management on the fundamental direction of the economy. One primary impact of management will certainly be to restrict the use of natural resources, but there will be several other secondary effects associated with the new increased scarcity value. These effects are based in the incentives for induced investments in innovations that could augment these scarce resources, and in the capital that embodies these innovations. These investments represent the change in the direction of the economy onto a new path of development, incorporating the recognised scarcity of the natural resources. Although the models of Stokey and Smulders intimated that these things were occurring within the managed economy, the focus was on the shift in the mix of goods and services.

We wish to expand our enquiry now to include the wider impacts of government intervention into resource management. One of the key issues examined by the growth literature concerns the manner in which societies are able to elect pathways dependent upon new technologies that do not yet exist. These resource-augmenting technologies are crucial for purposes of switching onto pathways that will enable greater resource consumption in the context of continued economic growth or sustained welfare. The issue examined concerns whether it is possible to induce these changes in technology, and whether environmental regulation has been an effective means of doing so. In this section, we will discuss the so-called "Porter hypothesis" and set out conditions under which environmental management is able to induce green growth.

4.1 The Porter Hypothesis: Environmental Policy and Induced Innovation

From the perspective of mainstream economics, an environmental problem is characterized by the misalignment of private and social costs. In such an instance, it is socially optimal to impose environmental regulation bringing in line the private and social costs. Although this policy is optimal from a welfare point of view, it oftentimes increases the costs for the polluter and may result in a loss of competitiveness for a particular industry; an argument often brought forward by politicians and interest groups. This is the "static impact" of intervention that was discussed in the preceding section.

Porter and Van der Linde [1995] challenges the notion that environmental regulation is costly, which they claim comes from a static view of regulation. They argue that stringent environmental regulation induces technological progress as firms adapt to the new conditions. In this dynamic framework, the gains from induced innovation (e.g. productivity gain, first mover advantages) may offset the costs of the imposed regulation, if properly designed. So, if there are potential profitable innovations, why do businesses not pick up those opportunities in the absence of regulation? Porter and Van der Linde [1995] claim that in a world with incomplete information and organizational inertia, firms cannot oversee the numerous potential opportunities for technological innovations. Pollution or waste is in their eyes often an indication of inefficiencies which creates room for improvement and innovation. Hence, there is a role to play for the government to set regulation which can induce innovations.

Porter and Van der Linde [1995] also give practical recommendations as to how those policies should be designed. First, policies should leave the concerned industry the leeway to take an appropriate approach to innovate; no standards such as “best available technology” should be imposed. Second, incentives should be set such that continuous improvement pays off rather than towards remaining with a particular technology. Third, policy should ensure as much certainty regarding the regulatory process as possible. These are all important means for enabling the industry concerned to search out the right path forward, in light of the signal received by reason of the introduction of management.

Palmer et al. [1995], representing the standard approach to resource economics, have been critical of this so-called ”Porter hypothesis”. They outline two assumptions which are necessary for the hypothesis to hold: For regulation to have positive private benefits, businesses have to overlook opportunities to realize profits and the government must be able to correct for this market failure. While Palmer et al. [1995] admit that technological innovation may in certain cases offsets the costs of regulation, they insist that environmental regulation is usually associated with costs and that the adequate tool for assessment of environmental policy is a cost-benefit analysis.

There is a substantial theoretical literature that examines this argument. Xepapadeas and De Zeeuw [1999] argue that a trade-off between stringent environmental regulation and competitiveness exists but this trade-off can be relaxed considerably. In a model which includes capital of different ages, the authors find three effects which decrease the costs of regulation to the firm: First, a downsizing of production, leads to an increase in prices. Second, the age composition of the capital stock changes towards newer machines which are more productive. Third, those effects taken together make the environmental aim feasible at a lower environmental tax as envisaged in a static view.

The previously introduced Porter Hypothesis argues that the impact of environmental regulation is simply to incentives industries to become more efficient, so that the aggregate impact is positive [Porter and Van der Linde, 1995]. Other economists have argued that, despite the secondary dynamic effects, the overall impact of environmental regulation on industry must be negative [Jaffe et al., 1995]. The point of environmental regulation, in their view, is whether the societal benefits from retaining environmental goods and services outweigh the industrial costs. This debate remains unsettled and a significant number of studies have been undertaken.

The previous discussion shows that the key to the Porter hypothesis is whether the dynamic effect of inducing technological progress (i.e. enhancing productivity) can outweigh the static effect of imposing a private cost on the regulated industry. In the next section, we discuss these two countervailing effects in a production possibility frontier framework.

4.2 The General Concept that Dynamic Effects Might Outweigh the Static in LR

Consider Figure 3 below. This is a representation of the “Production Possibilities Frontier’ (PPF) for a standard closed economy. It shows that the fundamental capital endowments of the society may be used to produce two sorts of goods – termed Good A and Good B. The fundamental difference between the two sorts of goods is that Good A uses a lot of environmental resources in its production (air, water, eco-systems) while Good B does not. We might think of Good A as being those goods and services deriving from traditional heavy industry (steel, chemicals, forestry or agriculture) while Good B as being those goods or services deriving from less environmentally intensive activities (financial services, retailing, light manufactures). The society concerned has a given endowment of physical capital (K), labour (L) and environmental resources (E) that are used in producing its entire national product. The same figure is generated again in Figure 4. The question that is addressed in both Figures 3 and 4 is: How does the advent of environmental regulation impact upon the productive economy? That is, how does the PPF respond to environmental regulation? We will see below that there is a diverse set of answers to this enquiry.

Standard Static View of Environmental Regulation

When there is no environmental regulation, the PPF will be represented by the heavy line in Figure 3. The absence of environmental regulation has the implicit effect of pricing environmental resources at zero. Any firm or industry wishing to use the air or water for disposal of its waste products or for production of its goods and services may do so without constraint. This maintains the PPF at the highest possible level of goods production (furthest from the origin).

The society might then decide that – for any number of reasons –it wishes to introduce environmental regulation. This may be because the society sees that there are alternative uses for the environmental resources, and so the opportunity costs of using them should not be zero. It might also be because the society sees that there is a failure to retain adequate environmental quality to operate the industries themselves efficiently. In any event, the advent of environmental regulation in this scenario creates a constraint on the previously unrestricted use of this factor of production. The impact of environmental regulation in this scenario is straightforward. It shifts in the PPF along the axis for Good A (the environmentally-intensive good). Although the economy remains capable of producing the same amount of Good B, it can no longer reach the same levels of production of Good A. In effect, the society has reserved some amounts of environmental resources for other uses, and these restrictions have reduced the level of production in the environmentally-intensive production sector. In this view, environmental regulation is a costly (to the production sector) method for maintaining environmental quality for some sectors of the society.

Induced Innovation View of Environmental Regulation – dynamic incentives

The induced innovation perspective on environmental regulation commences from the same starting point as the standard view – the initial impact of regulation is to place a price on the use of environmental resources and to shift in the PPF for goods based upon them. This view then deviates from the standard view by emphasising a second and dynamic effect, whereby the impact of pricing environmental resources is to create incentives for firms and industries to economise in their use of them. In effect, environmental regulation's main impact is to put industry to work on increasing the efficient use of environmental resources in their production systems. Before regulation, firms did not need to think of methods for economising upon these resources, but afterwards the firms must attempt to solve this problem in the course of their production efforts.

The impact of these dynamic incentives is to cause the PPF to shift twice – once inwards by reason of the pricing of environmental resources and once outwards by reason of the responsiveness and increased efficiency of new methods of production. (Figure 4) The aggregate impact of environmental regulation may be either negative or positive in aggregate, depending on which of the two effects outweighs the other.

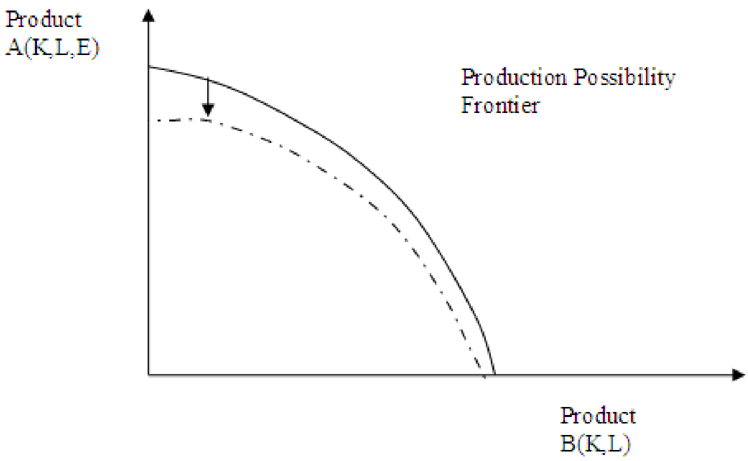

Figure 3: Static impact of environmental regulation.

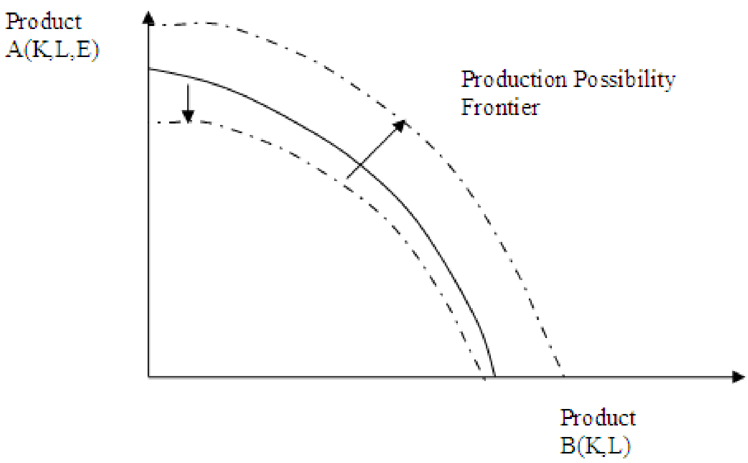

Figure 4: Dynamic impact of environmental regulation.

What conditions must inhere for the dynamic impacts of regulation to dominate? Mohr [2002] shows that the dynamic effects can outweigh the static effect in a framework with external economies of scale in production. Although technological progress can offset the costs of regulation in Mohr's model, the Porter hypothesis – 'increases in environmental quality and welfare – may be feasible but not always socially optimal.

In Mohr's model, the productivity of any firm using a particular technology increases with the industry's experience in this technology. This feature can result in a situation where a more productive and less polluting technology becomes available but it is not worthwhile for individual firms to switch. The new technology comes with a short term cost: Due to the lack of experience of the industry in the new technology, the productivity is initially lower than if the old technology was used. More formally: $f(l, w, K_f) > g(l, w, K_0)$ even if $f(l, w, K) < g(l, w, K)$ for any values of labour l, wage w and experience K. This feature of the model is illustrated in Figure 5. If the experience in the old technology is above $\tilde{K_f}$, there is a productivity cost attached to adopting the new technology as an early adopter.

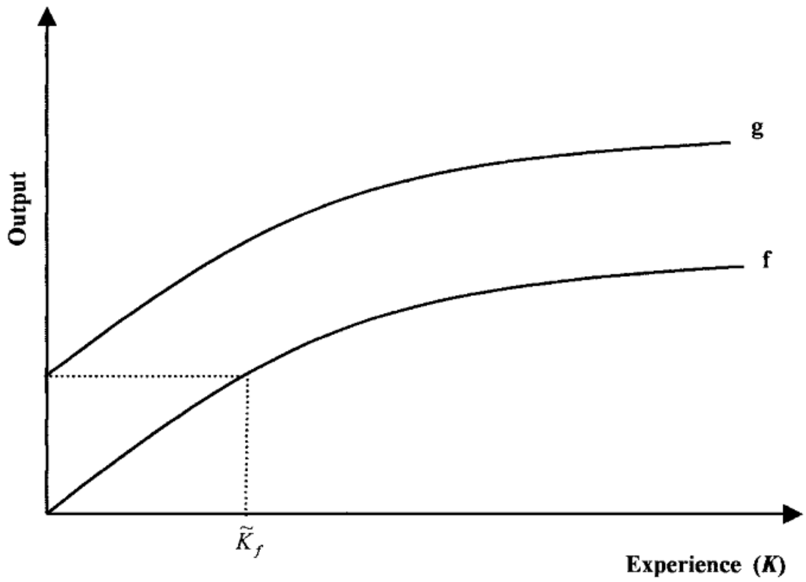

Figure 5: Output and industry experience, source: Mohr [2002].

When incentives favoring late adoption prevail (e.g. a cost for early adopters), environmental regulation can increase environmental quality and productivity at the same time. However, Mohr [2002] stresses that increasing output and reducing pollution is not necessarily optimal, even though this outcome can be achieved. The more productive technology results in an increased opportunity cost of abatement. If the marginal disutility of pollution does not increase accordingly, the optimal amount of pollution increases.

There is a large literature discussing the so-called Jevon's paradox or rebound effect: The paradox that the availability of a more resource-efficient technology may result in increased pollution. William Stanley Jevon first brought up this issue with regard to the coal question [Jevons, 1866]. At the end of the 19th century, the availability of engines which would efficiently use coal as input resulted in increased coal usage rather than a saving in coal. The idea is that the more energy-efficient technology lowers the cost of energy per unit of output and firms subsequently find it profitable to increase their energy consumption. This effect can partly or completely offset the efficiency gains [Greening et al., 2000]. In their survey of the empirical literature, Greening et al. [2000] only find a low to moderate rebound effect. Hence, the Jevon's paradox or rebound effect – although theoretically interesting – does not seem of great practical relevance to us in the question of the Porter hypothesis.

On a critical note, Mohr [2002] points to the similarity of the Porter hypothesis to the infant industry argument with a striking consequence: to adequately design regulation, regulatory authorities face considerable information requirements and have to resist the pressure from lobby groups. This argument has been previously put forward in the debate about strategic trade policy. For environmental regulation, it implies that the government has to guess the price paths of resources right to induce profitable technological innovation. The estimate of the price path includes two guesses; one concerning the future scarcities and environmental problems and one regarding potential foreign markets for induced innovations (i.e. which environmental issues will be strictly regulated in other countries). In addition to the informational requirements, governments also have to resist lobbying groups which may try to capture the regulatory authorities in their favor by either preventing regulation or demanding regulation for protective reasons.

We take from this section that the Porter hypothesis is theoretically feasible. Whether the hypothesis holds, ultimately depends upon the specific contextual conditions and remains an empirical question. In the next section, we summarize the empirical evidence regarding regulation and competitiveness.

4.3 Empirical Literature on National Pathways: Does Regulation induce Innovation?

The direct impact of environmental regulation is to raise the shadow price of the resource away from zero. This has the dynamic impact of making investment in resource-saving technologies worthwhile. The overall first effect is an increase in R&D spending in regard to resource conservation. This effect may be seen in a closer look at Figure 1 of the US data on the costs of environmental regulation [Jaffe et al., 1995]. In the most comprehensive study of production impacts, five per cent of the cost changes were found to flow from the increased R&D expenditures by the industries concerned.

Of the accounted-for costs of environmental regulation, approximately two thirds were costs

Sector	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Personal Consumption Abatement	10,278	10,307	12,119	13,270	14,251	15,349	13,159	14,316	12,278	10,455
Business Abatement	48,969	45,726	46,031	49,825	51,314	52,994	53,846	55,615	57,784	60,122
Government Abatement	16,446	75,912	15,504	16,760	17,684	18,974	20,727	20,559	21,560	23,122
Regulation & Monitoring	2,190	2,068	1,946	1,823	1,647	1,923	1,838	1,985	2,005	1,950
Research & Development	2,625	2,484	3,115	2,998	3,017	3,186	3,204	3,216	3,303	3,303
Total	80,509	76,495	78,713	84,677	87,914	92,425	92,773	95,694	96,928	99,024

Table 1: Expenditures for Pollution Abatement and Control (in millions of 1992 dollar), source: Rutledge and Leonard [1992] in Jaffe et al. [1995].

Case study	Directive (Sector)	Ex-ante/ex-post ratio Upstream
1	Large Combustion Plant Directive (LCPD) (Power sector)	2 (Germany)
2	Integrated Pollution Prevention and Control (IPPC) (Belgium Ceramics)	> 1.2 (operational costs) ≈1.1 (capital costs)
3	ODS (Ozone Depleting Substances)	2.5 (1.4 - 125)
4	Transport (Netherlands)	2 (1.4 - 6)
5	Packaging	-
6	Nitrates Directive (Agriculture)	≈2

Table 2: Declining Abatement Costs in Regulated Sectors, source: Oosterhuis [2006].

borne by the producers in terms of the new shadow price of the resource, while another twenty per cent on average were borne by consumers for the same reason. Only about two percent of the costs were institutional while another five per cent was invested into R&D on resource-conserving technologies.

More important than the investment of resources into R&D is the impact of those investments. It would be the hoped-for impact of such investments to shift down the costs of production, or (equivalently) to shift out the production possibilities frontier for a given level of resource usage. The former effect is visible in the decline of abatement costs over time in regulated sectors.

In a recent cross-EU study by Oosterhuis [2006], the authors charted the decline of abatement costs in several recently-regulated industries. They compared the costs of abatement ex ante (prior to regulation) to those existing ex post (after regulation was imposed). In general the finding was that the costs of abatement across sectors declined by a factor of two (see Table 2). The introduction of incentives to investigate and to implement resource-conserving technologies were effective in cutting production costs in half. It is often the case that cost-savings are readily found when incentives for them are introduced. This is the induced-innovation objective behind regulation-sourced resource pricing.

4.4 Conclusion – the Dynamic Impacts from Implementing Environmental Policies

The previous analysis shows that the Porter hypothesis is theoretically possible. Under certain conditions, the dynamic effect of inducing technological progress can offset the negative static effect. If it does not fully offset the costs from environmental regulation, the dynamic effect can at least considerably relax the trade-off between environmental regulation and competitiveness.

The empirical relationship between growth and environment indicates that anything is possible. The society involved simply has to make the choice of what sort of path of mixed production it wishes to pursue. Previous experience indicates that most developed countries have followed similar paths, in which there is an increasing demand for non-market goods during the experience of growth in market goods. Then the question concerns how to implement that chosen path.

Environmental regulation is a means for implementing a particular path towards development. It both provides the means for electing the mix of goods and services the society desires to produce (public and private), and also the sets of technologies and capital goods that produce them. It is important that this forward-looking role of environmental regulation is recognized. It is not enough for regulation to be a simple engineering matter of cleaning up already-existing messes from past production. The point of environmental regulation is more about selecting the path forward than it is about clearing up the path behind. The Porter hypothesis literature makes clear that environmental management is more about the dynamics of the choice of development path forward than about the static issues of clean up.

5 The Concept of Socially Optimal Timing for Environmental Innovation

5.1 The Social Planner and the Concept of Optimal Timing of Innovation

In this section we discuss the optimal timing of innovation from a social planner's perspective. This is another approach to the same question raised previously: when is it optimal to introduce resource management? Since we have argued that the more fundamental reason to introduce management is to induce a shift between technologies and capital investments, then the fundamental question concerning management concerns when innovation should occur. This is an issue that has been addressed as a question of both inter-generational fairness and an issue of competitiveness. With regard to fairness, we are examining the reasons why a current generation would incur the costs of investing now for the creation of technologies that will only benefit a future generation. With regard to competitiveness, we are examining the reasons why a state would want to be an early investor in the creation of new technologies, rather than a later adopter of those created by others. In this section we focus on the former issue concerning the fairness of investment timing: why should one generation invest for the primary benefit of another later generation?

Backstop Technology Model Revisited

This question is most easily considered by first thinking through the situation if there were no separation between generations, i.e. if one generation would in fact be around forever in order to internalise the benefits of any of its investments. How would such an infinitely lived generation decide when to invest in a new (or backstop) technology? To consider this question, let's assume that our economy is endowed with one non-renewable resource (e.g. coal) and a backstop technology (e.g. solar power) is available. The backstop technology can produce output (e.g. energy) without being depleted; however, at current resource prices it is not economically viable.

The social planner wishes to maximize the utility for the agents in the economy (the representative agent). She has to choose at each point in time whether it is worthwhile to stick to the production technology using the non-renewable resource at a given price, or to switch to the backstop technology. As discussed in chapter 2.1, the price path of optimal depletion of a non-renewable resource may be conceived as following the "Hoteling rule" in some sense. That is, the price of the resource increases over time such that the scarcity rent from the resource increases at the rate of the interest rate. Then the present value of the scarcity rent λ_t is constant over time. If we assume that this price path is known to the social planner initially, then the social

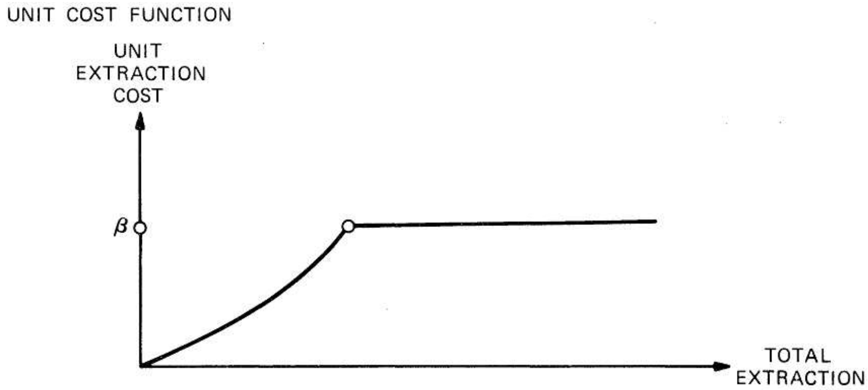

Figure 6: Unit cost function with backstop technology, source: Heal [1976].

planner can set the optimal time for the switch to the backstop technology (which is defined by its rental value relative to the current technology).

The "backstop technology" model looks something as follows: if the non-renewable resource is abundantly available. Its price is relatively low and large amounts of the resource are being extracted. At this point, society benefits from the cheap source of energy; the price of the backstop technology is prohibitively high compared to the non-renewable resource. As the price of the resource increases, less and less of the resource is being exploited. The social planner compares the resource price with the price of the backstop technology. At the point when production costs between the two technologies are equalized, the social planner decides to start using the backstop technology and both technologies are used. Once the resource price surpasses the price of the backstop, only the backstop is used.

The Choice of the Timing of Innovation

We have illustrated the path of extraction and the switch to the backstop technology in a simple framework of perfect information, with given parameter values. In this framework, the timing of innovation is simply a by-product of the choice of extraction path. However, it is also possible to conceive of the model in such a manner as to enable some of these parameters (the relative cost of the backstop for example) to be thought of themselves as choice variables. In this sense, the backstop technology may not be available at a given cost at a given time, but but may itself require investment for innovation to occur. In this setting, the cost to society from switching between the former path of resource extraction to the backstop technology is the cost of innovation, and may be incurred at the time that the society wishes the innovation to occur.

The social planner then faces considerations and trade-offs of the type prevalent in endogenous growth models (see chapter 2.2 and Smulders [2000]): how much will the society optimally invest in research and development which yields an innovation with some probability p ? As we saw in section 2, the answer to this question depends on the preferences of the society regarding the distribution of its consumption across time (i.e. preferences over inter-temporal substitution). Any manner of investment has the same basic effect - of deferring consumption by means of investing today for higher consumption in the future. Investing in R&D simply postpones current consumption in order to enhance the rate of innovation and so increase growth of consumption in the future. All societies have preferences over the amount and timing of consumption, and these preferences will in part determine the choice of the optimal timing of innovation.

There are a couple of production-based issues that contribute to the nature of this process of switching and substitution. First, it is important to recognise that there may be capital stock externalities (e.g. learning-by-doing) that contribute to the existence of "switching costs". For example, the costs of using a given backstop technology may decrease with experience as learning occurs or additional investments improve the technology. The former corresponds to a situation illustrated in Mohr [2002]. In such instances, the social planner can incentivize the adoption of the new technology and overcome the foot dragging of firms waiting for someone else to make the first move. We will see below how important such "research subsidies" can be in breaking path-dependence, and shifting economies between technology pathways.

Secondly, it is worth noting that, in the very long run, these backstop technologies must tend toward reliance upon renewable resource-based technologies. An economy can rely upon switches between nonrenewables for a considerably long time; however, as the numbers and types of nonrenewable resources are finite, this transition period cannot continue indefinitely. Eventually, in a steady state solution, the backstop technology must move toward reliance upon renewable inputs (or use infinitesemally small amounts of the resource with ever increasing productivity).

5.2 Factors Determining the Optimal Timing of Environmental Innovation – Allocating Resources Across Time and Fairness to Future Generations

In the previous section, we laid out the basis for the analysis of optimal timing from the perspective of the social planner (maximizing the utility for a representative agent in that society). For an infinitely lived agent, it does not matter at what point in time consumption occurs as long as its net present value is maximized. This simplification assumed away problems of fairness between generations. In this section, we will turn to this aspect and discuss how fairness considerations influence the decision of optimal timing.

The timing of innovation matters when we relax the assumption of an infinitively lived agent. Innovation requires investment in R&D by the currently living generations to benefit today's as well as future generations. If there is a reduced weight placed on the welfare of future generations, then the fact that benefits of the innovation are not entirely captured by the current generation creates an incentive to underinvest in R&D. Even if the current generation knows the true scarcity rent λ and, hence, the resource price over time, it is still not optimal for those currently living to invest in R&D such that the switch to the new technology occurs at the same time as a social planner would choose. Ideally, future generations would transfer part of their benefit to the current generation, such that the incentives for investments in R&D are set up optimally. Of course transfers from future to present generations are not possible. In this case, there is an argument that the government should correct for this failure of intertemporal transfer markets and set incentives to enhance investments in R&D.

The economic literature discusses the problem of resource allocation across time through "Overlapping Generations" Models (OLG). Conventional recommendations by economists for environmental policy stress the problem of the incorrect or non-valuation of environmental goods and services through markets. In a multiple generations set up, the problem goes beyond this valuation framework. [Howarth and Norgaard, 1992]. Howarth and Norgaard [1992] show in an

OLG framework that a policy of internalisation is not sufficient to achieve sustainability (defined as nondeclining consumption). Optimal valuation ensures that a Pareto optimal outcome is achieved (no generation can be made better off without making another generation worse off), but sustainability is more a matter of inter-generational distribution. When present generations care little about future generations, sustainability does not necessarily result. The authors show that a combination of policies is required - internalisation of externalities for efficiency and fairness for sustainability.

Another critical factor in ensuring sustainability is the application of the appropriate discount rate in determining the weights placed on welfare across generations. Marini and Scaramozzino [1995] discuss the trade-off between capital accumulation and the environment formally in an overlapping generations set-up. They derive the requirements for an optimal time-consistent fiscal policy; specifically, the condition that the age-weighted marginal utilities have to be equal across agents and the marginal social benefits of capital equated to the benefits from the environmental stock. They argue for the social rate of time preference should be used comprised of the pure government discount rate subtracted by the population growth and augmented by the pollution absorption capacity of the environment $\delta - n + m$; the rate gives larger weights to larger populations and also takes into account the absorption capacity of the environment. This is similar to the arguments of Smulders and others regarding the use of "own discount rates" of the environment, that make apparent the rate and manner in which natural capital is converted across the development path. A social discount rate that incorporates the marginal benefit of natural capital is important for the maintaining of natural capital stocks across generations.

In sum, the social choice of the timing of innovation balances several important factors: a) the society's willingness to smooth consumption across time; b) the society's willingness to give weight to future generations'welfare (fairness); and c) the society's willingness to place an emphasis on sustainability and natural capital. Innovation in this context is just one instrument for societal investment, and investment is just the means by which society smooths consumption across time. The same factors that determine how a society smooths consumption (time preference, consumption preferences) will determine its choice of innovation timing.

5.3 Optimal Innovation Policy Applied to the Environment

Now that we know why a society will choose a particular path of innovation, we need to investigate how such a pathway is implemented. That is, how does a government (efficiently) effect the timing of specific innovations? The literature on "Innovation Policy" considers these questions concerning the role of government intervention to generate inovation. The literature focuses on a) the demand side innovation policy (investment); b) the supply side of innovation policy (range of institutions undertaking R&D); and c) the nature of the government intervention required.

First, there is the reason for government intervention in the market for innovations. The argument is that such intervention is primarily required due to the difference in discount rates applied by the commercial and social sectors. Due to this difference, policies to invest in R&D in the long run are needed. Through regulatory requirements or targeted financial incentives (tax credits), incentives for innovations can be set up that reward long term investments through mechanisms other than the market.

Therefore, there is an important argument that direct investment is necessary at initial stages of research (basic research) when the value of research is high for society but the research is still distant from commercial application. This situation may also be the case if a specific problem has to be overcome but the success of particular research activities is highly uncertain. Furthermore, policies to support the adoption of early innovations should be implemented. Early innovations are often not as reliable as the currently used technologies and require high capital and operating expenses. Once, they are adopted learning-in-use effects may considerably increase their quality. In those instances, subsidies or other kinds of public support can facilitate their adoption.[Mowery et al., 2010].

Mowery et al. [2010] argue that an approach purely focused on the supply-side will not work, i.e. that states need to develop the supply side of innovation (i.e. the breadth and range of suppliers), not just the level of investment. Hence, policy makers should not in general try for a "big push" in a clearly specified direction of centralized research effort as in the Manhattan Project and the Apollo Project. Those centralized programs do not take into account the different nature of the challenge where potential technologies and also adopters are very diverse. These authors recommend that management intervention is more effective because it generates both the direction and the level of investment. This can be achieved through policies such as carbon taxes or cap and trade. These policies help to create a broad set of suppliers (as well as demanders for the development) of new technologies. Popp [2010] argue that this is essential especially for the adoption of innovations. In the face of the uncertainty associated with the technological developments, diversity and competition in R&D should be encouraged. This can be done through various policies such as prizes, awards and procurement competitions

How should a government intervene? What is its role? In addition to the breadth of the policy, it is also important that the number of instruments be appropriate. Resource pricing may be adequate to drive investment in the right direction, but insufficient to determine the correct amount of investment. It might be important to combine a resource-pricing strategy together with an innovation subsidy in order to achieve optimality in both the direction and the level of investment.

5.4 Conclusion – The Social Concept of the Optimal Timing of Innovation

This section has considered the issue of growth and resources from the innovation policy perspective. This is the area of economics concerned with the questions of the optimal level of social investment in innovation, and the optimal level of intervention in the direction of innovation.

The importance of investment in innovation is critical to the continuation of growth from a limited resource base. It is a matter of preparing the new technologies for the time when the shift from increasingly scarce natural resources is required. This is important both for the basic efficiency of the economy, and also as a matter of fairness to future generations. The current generation must always be laying the groundwork for living in the world of scarcity which its economy is generating.

What sort of innovation policy is necessary in order to address this fundamental need for new technologies? First and foremost, the innovation policy literature reaches the same conclusion as the resource management literature - what is required initially is intervention to correct for any failure to perceive existing resource scarcity. Interventions that increase the perceived price of the resource (through taxes or restrictions on use) will be internalised through the market, and create equivalent (present value) incentives to invest in the avoidance of this scarcity. This is important because it provides a basic but general signal to innovate away from the relevant scarcity, but without dictating the precise form of innovation. It generates the most general signal of the level and direction of innovation, but leaves the solution of the problem to the market.

But it is also critical to recognise that the market will fail to generate a complete response to this sort of intervention, because of the difference in discount rates. Markets are interested in providing near term solutions to problems, but are less amenable to long term investments with outcomes realised only in the distant future. These sorts of investments require more general subsidies to basic R&D, and perhaps even more directed and targeted forms of government intervention at this level. In fact, in general it is not possible to achieve both the direction and level of investment desired, without using two distinct instruments.

Overall, it is clear that innovation and investment is the key to a forward looking approach to the choice of development path. Government intervention is key to the creation of the initial incentives for such innovations, but the nature of this intervention is still basically sourced in the idea of resource management.

6 The Optimal Timing of Environmental Innovation – the National Perspective - Competitiveness

6.1 The Optimal Timing of Innovation from the National Perspective

Optimal Timing from the national perspective is very different from optimal timing from the social perspective – it is more like financial speculation on the movement of prices on a large market – nations that forecast these prices correctly will be able to choose paths that not only determine their own balance of consumption goods versus environmental goods, but will also anticipate the demands from other nations that will be making the same choices.

Competitiveness is about this first mover advantage in a broad sense of the term. It is about moving to a position that gives an advantage against other states who have not yet moved. In terms of innovation and environmental policy, the moves may be of one of two types: a) a move to a new resource price; or b) a move to a new resource policy. In this section we will examine both.

Lets consider the competitiveness issues of resource pricing within this first mover framework. First, we will assume that there is an actual resource scarcity value (λ), and an optimal value (λ^*) for every point in time (t), and every jurisdiction (i).

The actual value is the one that the government has in place via its extant environmental policy. This may be a system of actual resource prices, but it may just as well be constraints on use of the resource that drive up its scarcity (and hence it scarcity value). In any event, the actual scarcity value is the ultimate result of the aggregate impact of all environmental policies on the capacity of users to access the resource in that jurisdiction (i) at that particular point in time (t).

The optimal scarcity value of the resource is, on the other hand, a value that may not exist in practice in any given place (at any given time) but always exists in theory. It is a value that equates to the marginal opportunity costs of the resources implicit in its use. For example, the optimal scarcity value of fossil fuels would include not only the opportunity costs of alternative

Technology Leadership Game (aka Policy Leadership Game)			
		State i	
		λ	λ^*
State j	λ	archaic technology	state i as technology leader
	λ^*	state j as technology leader	technology frontier

Table 3: Strategic form game matrix.

uses of those fuels for energy, but also the opportunity costs of those carbon-based compounds as a sink of carbon dioxide (i.e. the value of unreleased carbon dioxide). There may be other costs arising from a given use of these resources of which we are not yet aware (as in the discovery of an ozone hole), and these costs should theoretically also be included in the optimal scarcity value of a given resource. The optimal scarcity value of a resource is the sum total of all societal costs implicit in its use in a given activity.

One object of environmental policy is to try to target actual scarcity values onto optimal scarcity values. The competitiveness value of environmental policy is to be found in being a first mover toward an actual scarcity value that is later adopted by many other states.

This is because actual scarcity value will generate investments in capital items that embed this value in those capital items. Capital of an earlier vintage will now be inefficient, because earlier vintages will be designed to use input combinations that are allocatively inefficient (geared to inefficient price ratios). Later adopters may then be at a disadvantage to the extent that a) they are late entering an already-developed industry; and b) they are late adopters of the efficient technology. First movers may have important advantages in both respects.

It is important to note that the concept of optimal scarcity value is something that is never knowable. The idea of competitiveness is based on the common belief that the actual scarcity value targeted by some states may be nearer to the true optimal scarcity value. It is in this sense that policy leadership is the ultimate strategic choice in terms of competitiveness, i.e. the point is to lead other states in the selection of the perceived optimal policy not some actual one. So long as other states are persuaded that your policy choice is the correct one, this is sufficient to generate a first mover advantage. In what follows, we will use a shift to the "optimal policy" to be representative of such a common belief in a given state's resource pricing policy.

Table 3 demonstrates how this first mover advantage operates. States that choose a particular environmental policy (or management system) will be moving their economies from λ to λ^* in anticipation of a "true" path of resource scarcity (λ^*_{it}) across time.

The adoption of the new policy-induced resource price λ^* will then induce technological changes that economize on the use of the resource at this new, higher level of scarcity. We would therefore expect technological change and investment in capital goods in country i that reflect the embedded resource scarcity price λ^*.

This new level of technology will have two effects: 1) it will determine a new level of exploitation of environmental goods and services in state i (therefore re-balancing the goods and service consumption in that state toward environmental goods and services) and 2) it will place

Effects of Environmental Regulations on Net Experts				
Study	Time period of analysis	Industrial Scope	Geographic Scope	Results
Grossmann and Kruger 1993	1987	Manufacturing	U.S. - Mexico Trade	Insignificant
Kalt 1988	1957-1977	78 industry categories	U.S. Trade	Insignificant
		Manufacturing		Significant
		Manufacturing w/o Chemicals		More Significant
Tobey 1960	1977	Mining paper, Chemicals, Steal, Metals	23 Nations	Insignificant

Table 4: Environmental Regulation and Export Competitiveness, source: Jaffe et al. [1995].

on the global market new capital goods that are valuable in a world in which resource scarcity is perceived to be near the price λ^*.

This second effect will render the state's goods and services more competitive on the world market, if either a) the state's forecast of resource scarcity turns out to be a relatively accurate forecast; or b) the state's forecast of resource scarcity turns out to be a relatively early adoption of that forecast (by other state's adopting the same forecast after it).

So, as set out in Table 3 above, if either state i or state j is able to make the first move to the optimal scarcity value, it achieves this competitiveness advantage. If both shift together, then both achieve the frontier without achieving advantage; and the converse is true if neither country shifts policies. Competitiveness benefits derive from either being the first mover, or avoiding being the second mover.

6.2 Evidence of the General Impact on Competitiveness

One of the important questions raised about environmental regulation concerns its aggregate impacts on industrial competitiveness. This is usually assessed by reference to overall trade impacts, and numerous studies have been undertaken to look at this. Most of these studies have been unable to discern any substantial effect of environmental regulation on export competitiveness. Table 4 reports some of these studies.

Overall, significant competitiveness impacts of environmental regulations are difficult to discern in empirical studies. Clearly there must be static production impacts from environmental regulation, but there are often countervailing benefits from regulation that are balancing these out. The studies do not demonstrate a clear negative impact on competitiveness.

Aggregate Impact of Environmental Regulation – Summing Up The first and most obvious impact of environmental regulation (that creates a non-zero shadow price to resource use) is to increase the production costs to environment-using industries. This must have the static effect of reducing the production possibilities in those industries that are resource-intensive. The second impact of environmental regulation is to enhance the incentives for investments to conserve on the use of these resources. This produces a dynamic impact – in which resource-conserving investments rise over time. A major research question has been the extent to which these two impacts - negative static plus positive dynamic - cancel one another out. That is, does the positive incentive to reduce use of the resource over- or under- compensate for the cost imposed upon the industry?

This is a research question that has been assessed empirically by numerous authors and studies. The mixed results of a recent study surveying the empirical work are set out in Figure 7.

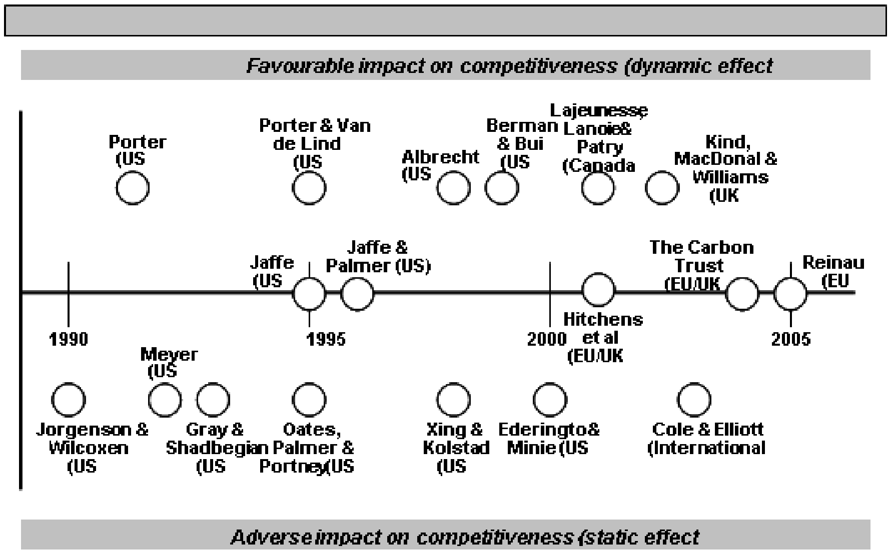

Figure 7: Studies on Aggregate Impact of Environmental Regulation, source: SQW [2005].

The one clear conclusion from this mix of evidence is that there is no necessarily positive or negative impact from environmental regulation. The outcome of environmental regulation depends too much on the hobjectives being pursued, and the manner of its implementation, to give an always-present outcome. If a regulator targets technological change and dynamic incentives, then it is likely that the outcomes of the regulation will be positive. If the targets are instead public good provision and social welfare, then it is possible that the production impacts are negative in aggregate.

In sum, the aggregate impacts of environmental regulation are not a given. At the outset of environmental regulation the objectives might very well be the basic pursuit of social welfare through public good provision (water quality and air quality for health and enjoyment). As environmental regulation progresses, the objectives can become much more complex, as technological change is induced and directed in the direction of social progress more generally. One of the important components of social progress is clearly social welfare but another is the pursuit of technological change. Environmental regulation can induce technological change. This may render a country a competitive advantage if its guesses regarding future environmental scarcities and hence the price paths of resources turns out to be correct.

6.3 Conclusion – Dynamic Impacts of State Intervention

In the previous section, we developed a framework for the optimal timing of innovation from a government's perspective. We argue that governments can create a competitive advantage for their economy by inducing technological innovation through environmental policy.[2]. This requires that governments guess the correct value of resource scarcity λ^* right. The exercise of making a guess about resource value is similar to financial speculation and should be undertaken with caution. Making the wrong guess of this value may turn out to be costly.

There are essentially two ways that a government's guess can turn out to be correct: Either its estimate is relatively close to the "true" optimal value of resource scarcity (λ^*), or that government manages to convince other governments that its estimate is nearest the true underlying value. If other countries implement similar regulation which anticipates the same value, the country which first developed the technologies for this particular resource pricing strategy has a competitive advantage and can capture the innovation rent for the technology in demand.

The summary of the empirical evidence shows that there is no clear effect of environmental regulation on competitiveness. Hence, there is no automatic effect that environmental policy will always lead to an advantage in competitiveness or green growth. This result indicates that environmental policy needs to be thoroughly designed. In the next section, we turn to the discussion under which conditions state intervention can lead to enhanced innovation and competitiveness. [3]

7 The Conditions Under which State Intervention can Lead to Enhanced Innovation and Competitiveness – Pathways to Green Economies

7.1 Investing to Capture Innovation Rents with Increasing Resource Scarcity

One of the primary reasons why states achieve competitiveness on the world stage is through technological innovation. There are much-reduced benefits from coming anything other than first in a new field. Being the first in the field generates innovation rents.

As described, the obtained competitiveness advantage turns on a) forecasting resource scarcity correctly; b) inducing innovations that embed that accurate forecast; and c) selling these innovations to states that either adopt the same policies after them (or to states living in a world in which the increased resource price is realized). Even if those conditions are fulfilled, it is not guaranteed that the original innovator captures the rents. To benefit from the innovation, property rights have to be assigned properly.

The value of innovation lies in the conjunction of two distinct events: a) the creation of an

[2]Also the choice of environmental policy instruments is crucial for competitiveness effects. In this paper, we will abstract from the technicalities of choice of policy instruments and their pass through on energy prices.

[3]Wright [1983] and Parry [2003] provide an interesting discussion regarding some practical policy issues: Among other questions of policy design and instrument choice, they discuss whether environmental taxes should deviate from the Pivouvian tax in the presence of induced innovation and what implications induced innovation could have on the choice of instruments.

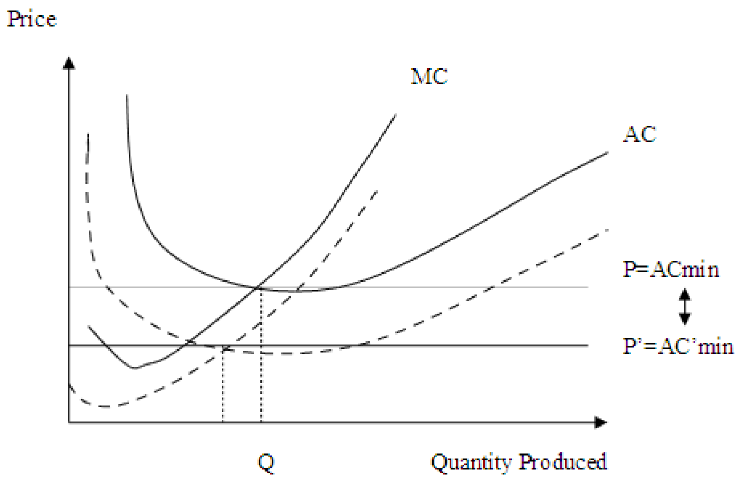

Figure 8: The Impact of an Innovation – industry equilibrium and rent capture.

idea or innovation that makes it possible to achieve some consumer welfare at a reduced cost; b) the ability to keep other firms from making use of this idea or innovation without permission (e.g. by taking of a patent).

Figure 8 assumes that the industry is an otherwise competitive one, with free entry and exit. This simply means that there are no barriers to markets, and all factors of production (resources, labour, capital) are available to any potential entrant. These are reasonable assumption with regard to most globalised industries. The initial level of production in such an industry is at Q, where the price of each unit is driven down to the minimum average cost of production (P=ACmin). This means that each plant in the industry is operating at an efficient scale, and selling at the same price.

The act of innovation may be represented by the shifting of the cost curves of a specific firm to the dashed lines set out in Figure 8. This means that this single firm has conceived of a way in which the same outcome (or output) may be achieved at a lower social cost – here represented by a shifting down of the cost of each unit of production (the dashed cost curves). If the innovating firm could not keep other firms from using the innovation, then the price of the good would fall to the new average cost (AC') and the consumers would capture all of the benefits (rents) of the innovation as worldwide price fell to the new (lower) average cost (AC'min).

Rent-capture is available if the innovating firm is able to prevent other firms from freely using its innovation, e.g. patents that make it possible for the innovating firm to prevent others from using its innovation without its permission. The innovating firm would then be able to charge every other firm a licensing fee (or "innovation rent") equivalent to the difference between the average costs (ACmin – ACmin') on each unit of production, thereby capturing all of the benefits from its innovation in these licensing fees. Importantly, the global industry would very likely to continue to operate as precisely as before, with the same number of firms, the same amount of global output and very likely the same amount of output per firm, but now the innovator would be able to appropriate an "innovation rent' on each unit of the good sold worldwide.

Then, in a sense, all of the firms in the industry would be working for the innovator. Their entry and continued operation in the industry continues only to the extent that they are able to generate this flow of licensing fees to the innovator. If the innovator feels that it is being cheated or disallowed its full rents by a firm, then it can simply withdraw its permission for the use of its technology and hence shut down the operation of that firm (since the firm cannot operate effectively in a global industry without the technology). Firms continuing in the industry may generate employment, production, and even dividends – but the only real rents in the industry are being captured by the innovator. In that sense, technology leadership equates with ownership.

The economic profits which accrue to the innovator depend on the cost of creation (investments in R&D), their desirability to the users, the market structure and the property rights. It is important to find a balance between the protection of property rights which creates incentives for innovation and also ensuring that the innovations can spread in the economy Maskus [2000]. The later is also crucial in inducing further innovations. If property rights are set to restrictive, innovations building on prior ones may be prevented.

The Mohr [2002] model which we previously discussed also demonstrates the importance of timing for capturing the innovation rent. If there are learning or experience effects in technologies, it may be costly to adopt too early. The productivity and opportunity costs accumulated over years or even decades may outweigh the rents captured from the innovation. The innovation has to be well-timed. In order to capture the rents from a innovation, one needs to build λ^* in the markets earlier than others and innovate first. On the other hand, being to much ahead of everyone else may be costly. Hence, the timing of the innovation is a delicate exercise which necessitates to be a couple of steps ahead but not too distant from competing industries in other countries.

So far there is an obvious point missing in our discussion. To capture the innovation rent, the innovation has to spread to other economies through a process of diffusion. Often times processes of diffusion are slow and a technology with superior performance and lower cost is not chosen over a currently applied one [Popp, 2010]. But this is not a process on auto-pilot. Governments can influence this process of diffusion. In the next section, we discuss the role of policy leadership in the adoption of environmental regulation.

7.2 Investing in Policy Leadership: Determining Rank in Order of Adoption

Technology leadership comes when a country is successful at a) creating unique innovations by making an investment in research and development (R&D) related to future scarcities that are not yet widely-perceived; and b) cementing leadership in those industries via the patenting of those innovations. When this is done successfully and other countries' industries wish to pursue those technologies, then they have little choice other than to license them from the technology leader. In this way, and in accord with Figure 8, a technology leader is able to appropriate the rents of innovation from others' need to follow that lead.

Why would other countries' industries wish to follow that lead? There are two fundamental reasons. First, it could be the case that the technology leader actually does bet on a particular form of resource scarcity in advance of its general recognition. Japan did this in the 1970s with regard to energy-conservation, and established a lead that is important now that the price of energy has increased significantly in real terms.

Another possibility is for a country to invest in a policy, and then see the policy diffuse across

Country	1970 - 1985	1985 - 2000
Sweden (11)	7	4
USA (10)	8	2
Japan (9)	8	1
Denmark (9)	5	4
Finland (8)	4	4
France (7)	5	2
Germany (7)	5	2
The Netherlands (7)	3	4
UK (6)	4	2
Canada (6)	2	4
	51	29

Table 5: Policy leadership in Environmental Regulation, source: Jänicke and Jacob [2004].

other states. This also happens in many cases, and is sometimes related to the change in real prices (e.g. in relation to energy) and is sometimes related to anticipating the directions that societies will move with growth and development. For example, societies with increased incomes often demonstrate increased demand for particular sorts of goods, such as leisure, recreation, nature, health and other environmentally-related goods. Establishing policy leadership in relation to the supply of these goods, and then having other states follow, can be sufficient to create technological and, consequently, industrial leadership.

More generally, the role of policy leadership is to anticipate the demands of the citizenry for changes in the sets of goods and services produced by the economy, and to establish the policies that will meet these demands. As societies change, grow and develop, it is predictable that their citizens want and need different things, rather than simply more of the same. For this reason the income-elasticities of different goods differ substantially over the course of development; some goods are demanded proportionally less as incomes rise (e.g. food) while others are demanded proportionally more as incomes rise (recreation, health, environment). One of the basic functions of environmental regulation is to anticipate these changes and to determine the relative proportions of different forms of goods and services produced by an economy [Stokey, 1998].

How do these policies which are initially set by policy leaders spread internationally? Kern et al. [2001] find empirical evidence that environmental policy innovations indeed spread internationally. This process can occur more or less rapidly. The authors identify three factors which constrain or enhance the diffusion process. In particular, national characteristics, the the international system and characteristics of the policy matter for the particular diffusion process.

In any event, states that anticipate future change and establish desired policies first have the ability to become policy leaders in the field, and hence potentially establish technology leadership as well. Since the inception of environmental regulation, the policy leaders in this field have been the Scandinavian countries, the USA and Japan (Table 5).

This policy leadership has often been translated into technology leadership, as industries respond to national policies with R&D and resultant patenting. The important consequence of such patenting concerns its adoption by others, and is represented by the proportion of patents won in other countries. This is demonstrated in Table 6, below, where it is shown that the majority of foreign patents in these fields have been won by the US and Japan.

Sources of foreign patents by nationality of inventor[a,b]												
Source	Industrial air				Water				Vehicle air			
	1972	1977	1982	1986/7	1972	1977	1982	1986/7	1972	1977	1982	1986/7
United States												
Japan	48%	28%	11%	38%	0%	21%	15%	23%	38%	82%	90%	35%
Germany	36	38	64	28	0	21	41	35	45	12	7	51
Other OECD	16	31	25	31	100	49	38	28	18	6	4	11
Other	0	0	0	3	0	9	6	3	0	0	0	2
Foreign/total in field	21%	32%	28%	32%	20%	33%	34%	26%	40%	66%	68%	65%
Japan												
United States	50%	46%	42%	64%	48%	44%	50%	83%	47%	33%	60%	100%
Germany	25	15	42	14	7	22	17	15	47	33	30	0
Other OECD	20	31	16	14	44	44	17	15	7	22	0	0
Other	0	0	0	0	0	0	17	0	0	0	0	0
Foreign/total in field	20%	13 %	19%	14%	27%	9%	6%	6%	15%	9%	10%	11%
Germany												
United States	37%	34%	45%	15%	40%	20%	22%	19%	35%	34%	70%	19%
Japan	48	34	16	27	10	14	11	3	50	48	11	27
Other OECD	13	32	37	58	50	61	57	71	15	8	20	46
Other	1	0	3	4	0	4	8	6	0	0	0	8
Foreign/total in field	71%	47%	38%	26%	50%	49%	37%	31%	52%	50%	56%	26%

a The percentages may not sum to one due to rounding.

b For Germany and Japan the last column year is 1986 to avoid possible biases due to differential truncation error across nationality of patentee.

Table 6: Technology Leadership Resulting from Policy Leadership, source: Lanjouw and Mody [1996].

Note that Germany (not as much of a policy leader as the US or Japan in these fields) needed to purchase the majority of its environmental technology from other states initially (71% in air, 50% in water, and 52% in auto emission), but then rapidly moved toward establishing technological leadership within its own borders. The US on the other hand was a technological leader in all three fields, but lost its advantage particularly in the case of automotive emission technologies. Japan started as a leader in these fields, and fortified its positions across the board. In particular, Japan became the clear technological leader in the case of automotive emissions, after starting out as a joint policy leader together with the US.

Despite these changing leads, it is important to recognise that the returns from initial policy leadership can be long-lasting, as important patents can have lifetimes of twenty years. It is possible to "innovate around' existing patents, but many times it is necessary to pay the licensing fees to the initial innovator in order to stay in the industry. So, even if a state establishes leadership only briefly, it may be living off of the rents of that leadership for decades.

These patterns demonstrate how policy leaders benefit from anticipating emerging trends. The first state to establish an important policy, which then diffuses to others, is presenting its industry with the opportunity to establish technological leadership in an important global industry. A policy-induced patent that is filed first is sufficient not only to grant that industry domestic leadership but also the opportunity to capture global rents once the policy diffuses.

7.3 Investing to Impact Exports by the Relative Rank of Technology Adoption

In the previous analysis, we showed that first mover advantages may provide rents to the innovator. From this perspective, there is little advantage from being anything than the first. The innovator patents the innovation and subsequently earns the innovation rent from whomever is applying this technology. A framework in which one can think of advantages accruing to later adopters is trade. One can think of instances where a relative advantage in technology also constitutes an advantage for home.

A theoretical economic literature of strategic trade analyses under which conditions profits may shift from foreign to home as a result of environmental regulation. Xepapadeas and De Zeeuw [1999], Ulph [1996], Simpson et al. [1996] find that it is theoretically feasible to come up with a set of conditions such that environmental policy leads to a shift of foreign rents to home. However, those conditions are oftentimes restrictive and the result should be considered with caution. In particular, Simpson et al. [1996] are skeptical of the idea that stricter environmental policy may lead to cost-reducing innovation to an extent that it offsets the costs. They find it "extremely dubious in practice" and state that R&D may be better suited as industrial policy in enhancing innovation.

What effects of environmental regulation realize in a strategic trade set-up depends largely on the market structure. Ulph [1996] shows that the results can be reversed depending on whether Cournot (firms set output) or Bertrand competition (firms set prices) is prevalent. All of the models which result in ecological dumping have assumed Cournot competition. When Bertrand competition is assumed, the result can be reversed and it may be optimal for governments to set stricter environmental regulation. Although Ulph [1996] stresses that market conduct (Bertrand or Cournot) is an important factor, he shows that it does not determine the outcome and the interaction with other factors is much richer. As a policy implication, it is hard for governments to know whether stricter or laxer environmental standards can lead to shift of profits from foreign to home.

7.4 Investing to Improve Firm Level Innovation

Innovation in general and environmental innovation in particular is fraught with uncertainty. Uncertainties are attached to the end-product, the reception of the innovation by the market, the extent to which the innovator can appropriate the gains, the regulatory impact and the end-result [Johnson and Lybecker, 2009].

Incentives to innovate may be constrained by those uncertainties or governance problems — and the government may intervene to remedy these. Microeconomic policy can promote firm level innovation. The two most prominent fields of policy action are intellectual property rights (IPR) and R&D, whereby the former is more controversial. There is an ongoing debate in the literature whether the IPR system enhances or hinders innovation. One can conceive several reasons why an IPR system may not perform as intended. First, patents can be used strategically and result in a lack of competition. Second, patents may inhibit constraints on further innovation (sequential innovation). Third, the IPR system may especially hinder entry for start-ups and constrain small firms. Fourth, competition to obtain a patent first may lead to inefficient R&D spending [Greenhalgh and Rogers, 2010].

Greenhalgh and Rogers [2010, p. 7-8] discuss several areas in which the patent system can be improved. The various suggestions have potentially different effects. In the following, we will only outline a few examples. Patent insurances can alleviate fears of litigation but can only be practically implemented in the framework of a compulsory scheme to avoid adverse selection. Improved efficiency of dispute resolution through independent IP offices may reduce costs by avoiding litigation. A lengthening of the protection period for patents may incentivize more innovation. Increased enforcement may have a similar effect. In conclusion, there are a variety of policies readily available to improve the performance of the IPR system in enhancing innovation. However, given the critics of the IPR system and its ambiguous effects, it remains unclear whether those reforms will be effective in fostering innovation.

In addition to the reform of IPR systems, alternative microeconomic policies exist to promote firm level innovation. Greenhalgh and Rogers [2010] point to R&D subsidies which can be implemented through the tax system as R&D tax credits. Most OECD countries already offer tax credits for R&D activities and empirical evidence shows their effectiveness in increasing research expenditures.

The previous discussion shows that it is important to set incentives to enhance innovation. The process of invention and innovation is fraught with uncertainty and market failures. If microeconomic policies do not sufficiently promote R&D activities by firms, an under-investment in R&D and consequently too little innovation occurs. A well-designed innovation policy consisting of a efficient IPR system and incentives for R&D spending, may deliver first mover advantages as discussed in section 7.1.

7.5 Investing to Enhance Potential Returns to Market R&D

In this last section we discuss this particular market failure, the lack of incentives to pursue basic research. Basic research stands at the beginning of a research process; it is an essential component for subsequent innovation and may open up new fields in which innovations can subsequently occur. At this early stage of research, the resulting findings are usually still distant from commercial application. Furthermore, findings are likely to be general and the value of the findings cannot be completely appropriated by the researcher. Usually, significant spill-over effects materialize from basic research which also benefit other firms. Therefore, private actors have little incentive to engage in this activity despite its importance.

We argue that basic research has an essential function in increasing the variability of technological innovations available. In a world with perfect information, a government can set research policy such that it incentivizes innovations which incorporates λ^*, the correct resource scarcity value. At the adequate point in time, the economy can switch to the innovation following the optimal paths of depletion of non-renewable resources (see section 5.1). Obviously, we do not live in the described world of perfect information and λ^* is unknown – the government has to make the guess $\widehat{\lambda^*}$. In the previous sections we learned that the domestic industry can gain from first mover advantages when the government's guess $\widehat{\lambda^*}$ is not far from the true λ^*.

However, what happens if the government turns out to be wrong in its guess? In this case, the capital of the economy may consist of machines which incorporate the wrong guess of the resource scarcity $\widehat{\lambda^*}$ and technology incorporating the true $\widehat{\lambda^*}$ may not be available. Such a situation may turn out very costly for society. It is at this point were another feature of basic research becomes crucial: Basic research does not only open up opportunities for research and development along the path according to the government's guess of $\widehat{\lambda^*}$ but also increases the variability of the research outcome, potentially incorporating different values of $\widehat{\lambda^*}$.

The outcome of basic research is uncertain. It does not always necessarily have a positive pay-off for society, but it may result in important innovations. Furthermore, we argue that importantly it also increases the variability in outcomes which increases the economy's ability to adapt if a different values of λ^* than expected materializes.

By supporting basic research, governments can increase the variability of outcomes. Those outcomes may or may not translate into subsequent innovations which are valuable on export markets. Nevertheless, the higher variability can help the economy adapt to corrected values of the resource scarcity λ^*. Policies to enhance basic research may take different forms; they may constitute direct subsidies to Universities or other research institutions or indirectly provide incentives through awards, prizes and other mechanisms.

7.6 Does induced innovation crowd out R&D funding?

In the previous sections, we discussed conditions under which governments can induce green innovation. The standard argument for intervention is that the social rate of return exceeds the private returns to the innovator. However, when governments induce innovations, this innovation may not come for free: What are the opportunity costs of this policy intervention? There are two separate issues which could emerge: Firstly, innovation subsidies or policies in favor of green technology may crowd out innovation in other sectors. Secondly, the innovations which are potentially crowded out may have higher spill-overs (i.e. a higher social value) than the ones induced by green innovation policies.

Goolsbee [1998] points to a practical problem in inducing innovation: A large fraction of R&D spending is salaries for research workers. Given that the supply of researchers is very inelastic (it takes years to accumulate the oftentimes very specialized human capital which is needed for research), much of the increase in direct research funding might not result in increased innovation activity but result in higher wages for researchers. Goolsbee [1998] shows for the US that indeed government R&D spending has resulted in higher wages (especially for scientists and engineers in defense research where a large fraction of direct US R&D funding takes place) and that therefore the effectiveness of R&D policy could be 30 per cent to 50 per cent lower than conventionally estimated. Through the increased wages, private innovation may be crowded out even in sectors and firms which do not receive government research funding [Goolsbee, 1998] .

More closely related to the Green Economy, Popp and Newell [2009] analyze crowding out from environmentally friendly R&D (more specifically GHG mitigation technologies). The authors find no evidence that R&D in unrelated sectors may be crowded out due to induced environmentally friendly innovation but some indicative evidence for crowding out within the energy sector. Examining closer the energy refinery companies in their sample, Popp and Newell [2009] find that the increase in alternative energy R&D comes at the expense of R&D in fossil fuel technologies (refining and drilling). Hence, induced environmentally friendly innovation does not only foster green innovation but also seems to crowd out R&D in dirty technologies. In pushing their analysis one step further, the authors examine the social returns to innovations which are crucial to grasping the crowding out effect. If the social returns of the innovations which are induced and crowded out are the same, then purely looking at the extent of crowding out can suffice. However, if the social returns are different, then an economic analysis only focusing on the extent of crowding out is misleading. There are good reasons to believe a priori that clean energy technologies might have a greater social value compared to other innovations. First, those technologies are at a relatively early stage and hence offer greater opportunities for ground breaking innovations which are associated with considerable spill-over effects. Second, energy technologies are used widely and can be qualified as General Purpose Technologies [Popp and Newell, 2009]. Based on patent data, the Popp and Newell [2009] find that alternative energy patents are more general (can be more widely used) but are not much higher in social value.

What we can take from this discussion is a sense of cautiousness in the design of policies which promote green R&D. The supply of researchers in green technologies is fairly inelastic in the short run and one cannot expect a sudden jump in research output by simply throwing more money at it. On the other hand, the results from Popp and Newell [2009] show that crowding out across sectors does not seem to be an issue. In addition, the crowding out effect within a sector at the expense of dirty technologies can be even seen as a welcome side-effect of induced green innovation if the social returns of those technologies which are crowded out do not exceed the the returns to green innovation.

8 The Conditions Under which State Intervention May Lead to Enhanced Competitiveness: Adaptation and Pathways to Green Economies

As described above, one route to enhanced competitiveness is increased innovation at the technology frontier, anticipating changes in policies or in shadow prices (or both) and investing to have the technology ready for those changes.

Another route forward is to adopt or to adapt the innovations of others to the conditions prevalent in the state concerned (or in its markets). This "diffusion-based" approach to green economies is more about the anticipation of future directions of innovation, and the investment in the capital stocks necessary to render the economy receptive to this direction of change. If the frontier is moving in the direction of the green economy, then investments much change now in order to be able to take advantage of this direction of change.

8.1 Investing in Adaptation: Frictions to Technology Diffusion and their Reduction

Economies which are not situated at the technological frontier can also gain from green innovation. In fact most countries are not at the technology frontier. From a global perspective, only a few countries have the capacity to innovate. For the others, foreign technology accounts for more than 90% of productivity increases [Keller, 2004]. Hence, if developing countries may not be able to innovate themselves, they can still benefit from the diffusion of technology bringing their firms closer to the technological frontier.

The diffusion literature commenced in agriculture and took off after the seminal paper of Ryan and Gross [1943]. The sociologists analyzed the diffusion of hybrid corn, an important agricultural innovation at the time, in two Iowa communities and gave rise to a new approach to communication research. The innovation was most importantly communicated through peer contact and its adoption took an S-shaped curve. Those who adopted first had a higher socio-economic status on average [Rogers, 1976].

In economics, Griliches [1957] pioneered the analyzes of innovation. Also analyzing the diffusion of hybrid seed corn, he shows evidence that much of the process of adaption and acceptance by entrepreneurs can be explained by profit maximizing behavior. More specifically, he found that the early or late development of adaptable hybrids and market entry of seed producers depends on the profitability of entry. The farmers also reacted rationally to the innovation: where profits were apparent, the innovation was rapidly adopted. Griliches [1957] analysis already included the idea that agricultural technologies have to be adapted to different markets.

Ruttan and Hayami [1973] raises the issue of adaptive capacity in the context of international technology diffusion: The large differential in agricultural productivity between countries together with some success stories resulted in a paradigm of "naive diffusion" or "extension bias" practiced by international donors. Those efforts only showed limited success; agricultural technologies which are effective in the US, are not necessarily suitable for tropical climates [Ruttan and Hayami, 1973]. This point is intuitively appealing and critical for the diffusion of technologies. When technologies are transfered, it is critical to ask whether those technologies are suited for the local conditions or how they can be adapted to fit those conditions. This argument extends to areas outside of agriculture. To benefit from technology diffusion even under different prevalent conditions, countries need to build the (research) capacity to adapt technologies to the local setting. For this reason, Ruttan and Hayami [1973, p. 121] stress the "national experiment-station capacity for adaptive research and development as a critical element in the international transfer or "naturalization" of agricultural technology".

We learned that technology cannot be always applied to other settings without adapting it. But how does technology actually spread? What are the mechanisms which enhance technology diffusion and which constrain it? In his review of the international technology diffusion literature, Keller [2004] identifies international trade and foreign direct investment as the two crucial channels of technology transfer. Evidence suggests that imports are an important channel for technology transfer. Technology learning seems less prevalent regarding exports, although also some indications for this exist. Foreign direct investment has been discussed as an important driver of technology transfer for a long time. From a theoretical perspective, this is plausible because FDI involves the transfer of firm-specific technologies, however, the empirical evidence of technological spill-overs mainly stems from case studies. Furthermore, proximity seems to matter for technological diffusion. The literature suggests that geography determines technology diffusion but has not found a consensus on what the economic meaning of the geography effect is (e.g. trade costs?). [Keller, 2004].

Some countries seem to be much more effective than others in adopting technology innovations. If the rich countries are more effective in adopting than poorer countries, this may in fact lead to a divergence with poor countries falling even more behind. Alternatively, it has also been suggested by Gerschenkron [1962] that poorer countries may benefit more from catching up [Keller, 2004]. Why is it that some countries are more effective than others in adopting technologies? Similar to Ruttan and Hayami [1973]'s argument, the literature points to human capital and R&D expenditures as an important factor. Both arguments basically can be brought down to the concept of absorptive capacity (i.e. successful adoption of technology requires a certain skill) [Keller, 2004].

Cohen and Levinthal [1989] argue that R&D has a dual role. In addition of generating innovations, R&D also increases the ability of firms to identify, assimilate and exploit existing knowledge. The authors back their argument with an analytical model and find empirical support for its testable implications. Nelson and Phelps [1966] formalized the idea that human capital matters in the diffusion of technology in two models. They argue that the better educated the manager the quicker she will introduce new production technologies. In their model, they introduce $A(t)$, the average index of technology and $T(t)$ the theoretical knowledge available which would constitute the best-practice if implemented. $T(t)$ advances at the exogenous exponential rate λ. In their first model, the lag between invention and practiced technology depends negatively on education h. $A(t) = T(t - w(h))$ whereby w denotes the lag. If h were constant also $T(t)$ increases at λ and the realized technological paths increases in education. The more rapid technological progress, the more it pays off to invest in education.

Benhabib and Spiegel [2005] extend on this framework. They implement two different functional forms for the diffusion process. When assuming an exponential diffusion process, economies grow at the same rate as the technological leader in the steady state. In the logistic specification, the diffusion process can be dampened and this allows for the possibility of a widening gap between the technological leading economy and the adopters. Benhabib and Spiegel [2005] test the specification and find support for the logistical model. They identify a minimum educational threshold for 1960 which is necessary for the catch-up. Their empirical analysis indeed suggests that most of those below the threshold fell further behind (22 of 27 countries). When they re-run the estimation for 1995, they find that most countries have progressed regarding education and that only four countries are still below the threshold. Mayer [2001] pursues an empirical analysis and also finds support that human capital matters for the adoption of technology.

From this discussion, we have learned that Human Capital and R&D spending can enhance the adaptive capacity of economies to adopt technological innovations. Additional to this, Jaffe and Stavins [1995] suggest that environmental regulation can also enhance the diffusion of technologies. The authors compare the effectiveness of different instruments of environmental policy in enhancing diffusion in the building sector. They find that market-based instruments perform better than conventional environmental policy in enhancing technological diffusion. Both energy taxes and adoption subsidies were found to have significant effects, whereby the later have stronger effects.

8.2 Investing into the Internal Diffusion of Innovation

New and more efficient technologies can only contribute to the growth of an economy to the extent that the technologies diffuse within an industry and firms adopt them [Hall and Khan, 2003, Hall, 2004]. The occurence of an invention does not automatically lead to widespread adoption. Processes of diffusion are rather slow and usually follow an S-shaped form. Two explanations are prevalent in the literature: The first stream of literature emphasizes heterogeneous valuation and declining or constant costs. At each point, firms compare costs and benefits of adopting and an increasing number of firms finds it worthwhile to adopt. The second group stresses effects of learning or epidemic effects. As time progresses more and more firms learn about the innovation from their peers and adopt it [Hall and Khan, 2003]. The government can influence the process of diffusion within its industries by setting incentives favoring the adoption of new technologies and removing market imperfections.

Market transformation refers to programs that are aimed at changing the structure and function of existing markets by encouraging the adoption of cost effective products and processes. Such programs encourage firms to move toward the "technological frontier' in their industry. The frontier represents the best practice in the industry, and corresponds to those firms with the most advanced or cost-effective technologies available. Market transformation programs diffuse frontier-level products and processes, and thereby improve overall industry performance, profitability and competitiveness. One of the fundamental roles for environmental regulation is to implement such a programme of market transformation, the diffusion of best practices across a particular industry, when there exists a wide variety of individual practices or technologies.

Why do industries often contain firms that are operating inefficiently? This sort of inefficient variety sometimes results when industries make capital investment decisions based on the information available at a given time, and this capital choice embodies the information and regulation extant at the time. With the passage of time, new information may arise that will cause new capital choices to be better. However, without regulation, there is the incentive for firms to maintain the inefficient capital in use for its lifetime, even if its social costs far outweigh its private benefits.

The simple fact is that there will be some firms who will be building new plants at the time of the new information (e.g. a new price or new environmental problem), and so their decisions will be based upon current-best information. Other firms in the same market place will have invested in the past year or two, and their decisions will not incorporate current conditions. In order to earn a return on invested capital, they will elect to ignore current conditions, unless they are forced to internalize them. For this reason, an industry producing the same products by substantially identical processes, may have completely different levels of energy use or externality generation.

Market transformation programs operate by shifting the range of production processes towards the first-best "technology frontier", and by narrowing the range of processes extant in the industry. They may do this by simply mandating the movement of technological choices toward the "best technology", or by using market-based instruments such as labeling or other information campaigns.

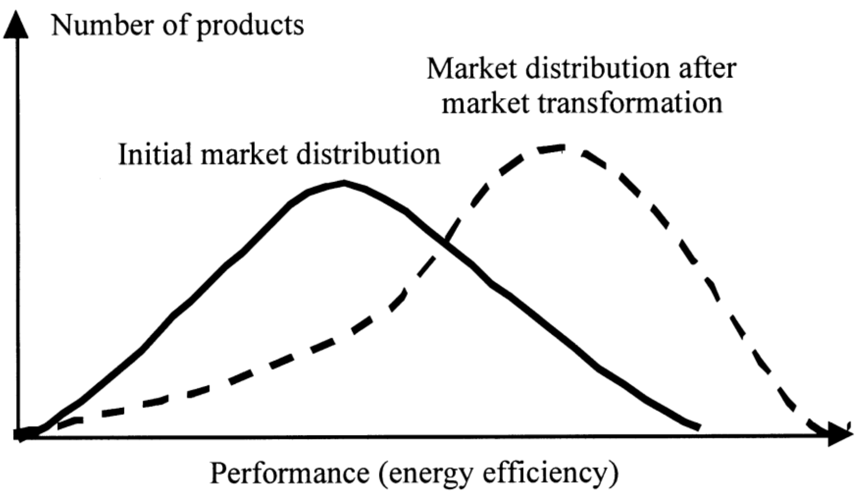

Figure 9: Market transformation objective – moving and narrowing technological choices, source.: Neij [2001, p. 68].

As depicted in Figure 9 below, market transformation programs create a permanent shift in the market towards the technological frontier (here, the more energy-efficient products and services).

Why don't market forces cause firms to adopt first-best technologies as and when they become available? This is usually the result of some failure in the supply of information, either firms do not know of the first-best technologies or the purchasers of their products do not recognize that the products have been produced with inefficient technologies. When information failures occur, first-best technologies can be slow to diffuse throughout an industry resulting in inefficiency and non-competitiveness at many firms.

When this occurs, it is possible to disseminate the required information directly through the government, and transform the industry simply by making it mandatory to act upon the new information.

Imperfect information may also be driven by skepticism regarding claims of expected cost savings and entrenched attitudes of management. That is, even when information on cost saving technologies is disseminated, uptake can still be poor due to a perceived lack of credibility. This means that the market may sometimes provide information but that there is still an important role for some manner of certification, i.e. some means of sorting out between valid and reliable information and general noise and advertising. In such a case, these failures may be detected and potentially resolved through some governmental intervention that will certify relevant information.

Another market failure that may constrain firms from moving toward the technological frontier is an imperfect credit market. When small businesses have limited access to credit (and most do) they may be unable to purchase new technologies which would reduce their costs and move them to the frontier. Banks may not be willing to finance the replacement of capital stocks long before they have been fully depreciated. This might be addressed by requiring banks to undertake audits of firms prior to issuing loans. In summary, there are market failures, most of them related to information problems, that may call for government intervention to transform markets (move the individual firms toward the technological frontier). Market transformation can lead to both better products for consumers and a competitive advantage for businesses through reduced costs of the average product.

8.3 Investing to Impact Exports by Harmonizing with Other Countries

It is increasingly important to adopt common standards because industry exists within an increasingly globalised economy. Not long ago it was possible for each state to make many of its own choices in regard to social, environmental and industrial regulation - without consideration for how other states made those same choices. To some extent, global trade was driven by the proliferation of heterogeneous standards in matters of domestic concerns (such as labour standards or environmental standards).

This has changed with the increased movement of goods, services, capital, corporations and technologies. It is reasonable for those involved – at any of these levels – to expect some reasonable level of conformity to common standards. Just because firms increasingly distribute different parts of the production process across different parts of the world does not mean that consumers expect that the end product will be much different. Regulators in the consumer states have an obligation to ensure that products meet local standards, irrespective of the places from which they are derived.

In addition, firms that span many jurisdictions usually have the incentive to impose commonality across their entire organisation, simply to organise it. Even if the various states hosting the various parts of a multi-national corporation (MNC) have very different regulations in place, it is often in the interest of the MNC to simply impose a common standard across the organisation. The single standard that will satisfy all jurisdictions is the highest one.

States that wish to participate in global trade and commerce will be best-served if they anticipate that these expectations regarding harmonisation will be placed upon them. Being outward looking in regards to some parts of global commerce implies some obligation to be somewhat outward-looking in regards to the whole of global production.

Finally, it is also important to recognize that standards often imply the acceptance or rejection of particular technologies. This is important because some technologies diffuse more readily than others. States might also decide to harmonize standards toward technologies that they view as important for advance progress in a particular industry.

If we analyze the impact of environmental regulation in a standard Ricardian trade model in which trade is driven by the differences in technology, we find that home may suffer from a negative static impact of environmental regulation on trade. Environmental regulations imply restrictions on the production technology of a country. Hence, the production possibility frontier shifts inward as we have seen in Figure 3. The inward shift implies reduced output and hence also reduced exports if the comparative advantage of the home country was in the pollution intensive good (the production technologies become more similar which decreases the gains from trade). If the comparative advantage of home was in the clean technology, the production technologies of home and foreign become more dissimilar and the environmental regulation enhances trade – however – output is still reduced.

Despite a negative static impact from the environmental regulation on output, long-term gains may emerge from environmental regulation. In a globalized world, exporters need to be in touch with the demands of the regulators and consumers in foreign markets. If strict environmental standards are demanded by the consumers in foreign markets or even imposed by foreign governments, exports may drop if they do no longer meet the standards expected by the foreign markets. More specifically, if a country produces a good using particular pollutants as an input in production which is prohibited by the foreign regulator or not desired by the consumers in a potential destination market, this market may be closed for exports. To guarantee the access to all potential export markets, a government has to apply the highest standard prevalent in the export markets. The commercial opportunities which open up when firms can access all foreign markets may outweigh the negative static effect of environmental regulation.

8.4 State Intervention for Enhanced Competitiveness: Adaptation to the Green Economy

Innovations are widely perceived as discrete improvements over previous products or processes. The notion of innovation should be set broader. The understanding what role innovation plays in developing countries and what the requirements are to trigger wider effects may prove crucial for policy making. Two empirical regularities are striking: First, small and informal improvements have been cumulatively as important for growth as discrete innovations. Second, interdependencies and complementarities play an important role in innovation. Those two empirical realities have substantial implications for the design of innovation policy [Trajtenberg, 2009].

In the first section of this chapter, we learned that innovations oftentimes cannot be plugged in a new environment without adoptions. The ability to adapt innovations to the local environment varies between countries and is crucial for innovation policy, especially in a developing country context. In the previous discussion we explored the role of human capital and R&D in enhancing the ability to adapt innovations.

Trajtenberg [2009] outlines policy recommendations regarding four key issues for developing countries: Skills, incentives, access to information and availability of finance. Those issues go beyond the usual recommendations and can be decisive for a innovation-based growth strategy to succeed.

Skills

The wide availability of skills is crucial to the different stages of innovation and its implementation. Skills as Trajtenberg [2009] refers to them comprise a wide spectrum of capabilities including basic skills such as literacy, more sophisticated skills which are necessary for innovation as well as managerial skills. Those skills can be acquired through formal vocational training and education and learning by doing. The occurrence of innovation results in demand for advanced skills. Those should be endogenously provided by the educational system. Hence, a key role for policy making is the provision of the public good education and also to ensure that the educational and vocational system is responsive to the demands brought about by innovations. It is essential that markets and institutions react by providing the kinds of skills which are in demand. The later point seems obvious but it is not when considering the isolation of the educational sector from changing demands in many countries. The educational sector should itself not just confine to reacting to demands but even anticipate them [Trajtenberg, 2009].

Incentives

At the beginning of an innovation always stands an innovator who decides to try something new. It is decisive that policies are designed in such a way that incentives are favoring innovation. Usually, innovation entails a cost – if the innovator cannot expect to appropriate the gains, innovation is dampened. This issue entails the question of IPR but extends beyond this issue. In developing countries, innovations have been historically dispersed among sectors, occupations and hierarchical levels. Potential innovators should either have a stake in the gains of their innovation or should be rewarded through other mechanisms (e.g. move up in the hierarchy). Setting the right incentives for innovation in developing countries translates into promoting inclusion and openness [Trajtenberg, 2009].

Access to information

A wide set of information is required for innovation. Potential innovators need to information on the available technologies, manufacturing requirements, market conditions and potential markets for the innovation. Innovation is often a result of a recombination of ideas [Weitzman, 1998] and therefore requires an overview of those. As a consequence, access to information is crucial. Policy can enhance the access to information in a variety of ways. It can for instance encourage knowledge intermediaries, create a vivid media environment through competition or support continued education. To access and process information, education (e.g. basic knowledge of English) is essential [Trajtenberg, 2009].

Availability of finance

Innovations are characterized by an information asymmetry between the creditor or investor and the innovator. The innovator knows the technical details of her innovation, the inherent problems and opportunities. This information asymmetry gives rise to a funding gap which is already prevalent in developed countries. Developing countries usually have quite constrained credit markets – especially for funding small enterprises – to start with. The problem is compounded by the fact that innovations carry inherent risks and the absence of collateral. This results in an even more difficult situation regarding the access to finance. The government can remedy by providing funding to innovation. In designing a financial support scheme, attention has to be paid to balance the incentives to innovators and avoiding moral hazard and corruption [Trajtenberg, 2009].

In the above discussion, we have outlined how economies which are not at the technology frontier can still benefit from green innovation. In addition to the previous discussion, we argue that the anticipation of future direction of innovation is also important for economies which are currently not at the frontier.

In section 6.1, we introduced a framework in which governments make guesses about future scarcities λ or price paths of resources. We argued that by anticipating future resource prices, governments can induce technological progress at the frontier. However, the anticipation of the future scarcities is not only important for economies at the frontier. Physical and human capital incorporates the current technological content. Depending on the sector and the specific application, capital remains in use sometimes for several decades (e.g. energy sector).

By not making an explicit guess of the future scarcities, one implicitly assumes that the scarcities in the future will be the same as today. In a changing world, this guess must be wrong and it implies that an economy may be stuck with machines which incorporate the wrong "underlying resource scarcities". This in turn may create costs for the economy and constrain growth. It may also make it harder to adopt technologies from the innovating economies if those are developed into a different direction. On the contrary, if future scarcities are anticipated, the economy is also well suited to benefit from technologies which were developed in countries at the technological frontier.

As a consequence, it is important for governments to anticipate future directions of innovation, and to direct investment in the capital stocks necessary to render the economy receptive to this direction of change. If the frontier is moving in the direction of the green economy, then investments much change now in order to be able to take advantage of this direction of change.

9 Coordinated Action for the Green Economy: What States can do together

One aspect of the move to the Green Economy is based in competitiveness, but another aspect is based in cooperation. Shifts between capital stocks can also be beneficial for all concerned if undertaken in a coordinated fashion. This is because of the many "network" and "lock in" effects associated with technological direction – and the role of coordinated action in achieving jointly beneficial change.

9.1 Network effects, lock in effects and coordinated action

The relation between technological innovation and growth is complex and characterized by a multiplicity of dynamic linkages. Those linkages involve interdependencies in the processes of scientific discovery and inventions and innovative economic activities as well as with political, legal and social institutions. One cannot expect investments in the science, technology and innovation subsystem to automatically yield growth [Aghion et al., 2009].

Those interlinkages in a complex system are characterized by innovational complementarities, network effects and can potentially result in lock ins into suboptimal equilibria. Complementarities become most salient in the context of General Purpose Technologies (GPT) but may also exist in other situations. GPTs can constitute an engine of growth for developing countries if well-designed policies which promote the adoption and the unfolding of innovational complementarities are implemented. Advances in the adopting sector can positively feedback to the GPT sector and create a self-enhancing loop [Trajtenberg, 2009].

Bresnahan and Trajtenberg [1995] introduced GPTs as technologies which are pervasive, have an inherent potential technical improvement and are complementary to applicative innovations. GPTs include examples such as the steam engine, electricity and others and have had an enormous effect on economic development. They can be potentially used in a wide range of sectors and are characterized by "innovational complementarities", i.e. they increase the productivity of research in downstream sectors. Innovational complementarities give rise to increasing returns to scale and result in opportunities and problems for economic growth. Because the benefits and new opportunities from GPTs are widely dispersed in different sectors, it is hard to coordinate and set adequate incentives for innovation in GPTs and its applications Bresnahan and Trajtenberg [1995].

In a situation where complements are important, efforts to enhance innovation by supporting private R&D investments are likely to be unsuccessful or to be dampened by negative feedback effects. As a consequence, complementary policy interventions are needed to create positive feedbacks or at least to remedy negative ones. This implies institutional reforms which are not easy to pursue and are potentially against their interest and provoke auto-protective responses [Aghion et al., 2009].

The practical implementation of technology policy in this context is confronted with great difficulties. The incremental evolution of a complex technological system can result in a bad coordination equilibrium (lock in) of which agents would like to escape. However, individual agents may not find it beneficial to depart from such an equilibrium when everyone benefits from strong coordination externalities even if a better technological solution becomes available [Aghion et al., 2009].

Such lock in situations can arise in situations in which there are increasing returns to the adoption of a particular technology. Experience may increase with adoption and hence improve the technology. If several technologies compete, a random historical event may shift the adoption process towards one of them. In such a setting, a technology may be favored which is inferior in the long-run. Hence, in the presence of increasing returns, the economy may lock itself in an inferior outcome. It may not be easy to depart from this outcome or to entirely predict it ex ante [Arthur, 1989]. Lock-ins can occur also through the development of competence in a particular direction. If firms accumulate competence in a technology which at some point becomes inferior to its alternatives but the firms can continue to operate successfully, a lock-in occurs. Based on their accumulated competence in one technology, firms may not consider radical departures from this technology – even if this is an inferior outcome. Government intervention can address this issue through support to basic research, procurement policies and investing in human capital Malerba [2009].

Network effects arise is situations in which a product has little or no value in isolation. This is the case when goods are strongly complementary (e.g. a certain video player and a certain type of tape) or when the size of the network determines the benefit (e.g. owning a facsimile machine). Cooperation or standards can be beneficial in two situations: First, in the presence of communication networks, the more users join the network, the more valuable it gets implying network externalities. Second, when consumers buy durable hardware which is related to a software component. The availability of software then depends on the purchasing choices of other consumers. In those settings, an equilibrium can expected which diverges from the social optimum [Katz and Shapiro, 1994].

The above discussion illustrates that networks effects and lock-ins can lead to non-optimal outcomes. In some instances governments may be able to remedy these problems at the national level. However, in today's globalized world this is not always the case. Oftentimes, networks do not stop at the national border but are global. Furthermore, lock-ins may not just occur nationally but may involve several economies or the entire world economy. Let's assume one's guess about the future resource scarcity λ^* turns out to be incorrect and this guess has to be corrected after several decades due to a new discovery (say climate change). In such an instance, the present capital incorporates old technology which was based on a incorrect guess of λ^*. The equilibrium is clearly nonoptimal but it may be impossible for a single economy to leave this paths of technological development (for instance due to little experience and competences in other technologies). In such instances, coordinated action between states can help to push the economy to a new technological path. If several economies undertake the change together, they can benefit from network externalities and also overcome competence lock-ins.

9.2 Economies of scale, learning by doing and aggregated markets

Small economies face different challenges than larger ones. The argument that the economy benefits from spillovers and externalities of R&D activities is accurate for large economies. Larger economies usually trade only a small portion of GDP, thereby ensuring that most of the benefits from spillovers accrue to domestic agents. Small economies, however, may see a large fraction of the spillovers and externalities "leaking" abroad and benefiting other countries. Hence, enhancing domestic invention and innovation activities does not necessarily boost growth to its full potential for small economies – although leading to growth in the research sector and contributing to global growth. At the same time, small and open economies benefit largely from international R&D spillovers [Trajtenberg, 2009].

The perception that in a globalized world, the relevant markets for innovators are global is not adequate when considering developing countries needs. It may be still desirable to target for local innovation and this may even be critical for growth in those regions. Hetereogeneity of preferences and needs in fact may require tailor-made innovations for the local context. Local needs and local markets do not imply little importance, in fact, local may refer to a large fraction of the global population. From this opportunities for both profits and maximizing consumer surplus can arise. For instance, developing countries needs regarding ICT may be rather sturdiness and backward compatibility than new features [Trajtenberg, 2009].

As we discussed in the previous chapter, technology which was developed in industrial countries may have to be changed or adapted to local conditions to serve developing countries' needs. In the presence of economies of scales, learning effects or small domestic markets, firms in a single country may not find it profitable to innovate in green technologies which are adapted to local needs. In those instances, international cooperation between states can yield beneficial outcomes.

The previously discussed Mohr [2002] model demonstrates gains from cooperation in the presence of learning effects. In the model, the productivity of a new technology depends on the aggregate experience (learning by doing) of the industry in this particular technology. Situations may emerge in which it does not pay off for a single sector to adopt a green and more productive technology simply because no previous experience in the technology exists. The first adopter faces a productivity cost. In this case, coordination can achieve a better outcome. If firms switch at the same time to the new technology, the transition phase can be shortened and the productivity penalty to the individual firm is shortened. In some instance, it may be sufficient to coordinate nationally. In other instances, national coordination may not be enough to quickly create sufficient learning effects and international cooperation is needed.

Aghion et al. [2009] argue that coordination is needed not only on the supply side but also on the demand side. This argument is crucial for the developing economies' context, small developing economies which are characterized by small aggregated markets may face similar technological needs. By cooperation, they increase the aggregate size of the market and thus demand for locally suited innovation which may trigger technological progress.

Economies of scales and learning by doing yield beneficial effects to the economy when they are realized. However, a small country may find itself in a situation where its domestic market is not sufficiently large to make upfront investments worthwhile or to provide a critical mass of firms such that learning by doing effects are realized quickly. In such cases, the international cooperation between governments can be crucial in providing a sufficiently large aggregate market to enable the recovery of fixed costs and to accelerate learning by doing effects.

9.3 State intervention for Enhanced Social Benefits: The role of mutual commitment in making technological changes

The previous discussion illustrates that situations can emerge in which it is not worthwhile for one economy to innovate even though the benefits to the region or the world could be outweigh the costs. Mutual commitment can serve as a device to overcome such situations of inertia.

Research and development activities create externalities and spillover effects beyond the benefits which can be appropriated by the innovator. Coe and Helpman [1995] find that total factor productivity depends on both domestic R&D capital stocks and the R&D capital stock of the trading partners. For large countries, the elasticity with respect to domestic R&D is larger than the elasticity to foreign R&D. This implies that domestic research efforts can enhance total factor productivity and provides a rationale for government intervention. To increase domestic welfare, the government may subsidize or incentivize research and development in ways which were discussed in section 7.4.

However, for small countries the situation is different. The authors find that for those the elasticity to foreign R&D capital stocks is larger than the elasticity to domestic capital stocks. So, why should domestic agents invest in domestic R&D when the benefits accrued by international spillovers matter more? Indeed, when only taking domestic benefits into account, they may not find it worthwhile undertaking investments in research and development. But at the same time Coe and Helpman [1995] find that especially small countries benefit from international R&D spillovers. Hence, small countries can benefit from cooperation.

Mutual commitments may break this initial inertia. Once a group of small countries which is interlinked by strong trade relations commits to undertake R&D effort, the members of the group can benefit from the spill-overs of their counterparts. Mutual commitments can also be beneficial in other previously discussed issues of this chapter. Network effects, lock ins, economies of scale, learning by doing, small markets sometimes cannot be sufficiently addressed at the national level but cooperation between states may make a difference.

10 Conclusion- Paths to Green Economies

In this paper we have surveyed the economics literatures in the areas of growth, sustainability and innovation policy - in order to provide a framework for thinking about the determinants of pathways to sustainable economies. The economic framework provides a useful way for thinking about these questions because it has framed the issue as one of choosing the right technologies at the right time, and investing in the capital goods that embody those technologies. The question of the "right technology" concerns the perceived path of future resource scarcity - and the creation of mechanisms that will induce investments in technologies that are responsive to that perceived scarcity.

Economics argues that "environmental management" is about the creation of these future paths, moreso than it is about dealing with past problems. Environmental management is the term of art for any manner of regulation or restriction that causes the economy to recognise and perceive the correct path of future resource scarcity. For example, this means that the role of a carbon tax is to create a belief in a future price path for the use of carbon that will induce investments in technologies that would rely upon carbon to a reduced extent.

Government intervention is therefore key to the choice of the development path for a society. A state must make the choice of when to intervene to turn that economy onto a different path - based on its own estimation of the sorts of resource scarcities that are important and missing from markets. Again, carbon is instructive, as fossil fuel futures prices will extend decades into the future, but without the incorporation of any impacts on other resources (such as the climate or the atmosphere). It is state intervention that will determine the extent to which these sorts of scarcities are being built into the economy (the technologies and the capital goods) at the present time.

In addition, government intervention may also be important to correct for other problems well known within innovation policy, such as the incomplete appropriation of information externalities. For this reason, environmental management is key to the inducement of technological change, but other more direct forms of government intervention (such as patents or subsidies) might also be important.

Finally, the economic framework also provides the means for answering whether intervention to move onto a different development path is optimal for a society, or welfare improving. It is clear that there is an important issue of inter-generational fairness at the base of this question. Current generations should be responsible for investing now in order to provide future generations with the technologies they will need for the scarcities currently being created. It can also be welfare-improving for a society to do this now because the society might prefer a different mix of goods and services (consumption vs. environmental) from the one that is being generated by the current economy.

Then it is also the case that government intervention to shift an economy onto a forward-looking pathway is important to provide an economy with the capability to innovate and to appropriate innovations. Innovation is important to economies in general, and interventions to improve the rate of technological change (and the capacity for technological change) are important general economic improvements. Environmental management may serve the purpose of pointing the direction for change down a particular pathway. Governmental intervention for innovation in general encourages a higher rate of change.

In summary, electing pathways to green economies - in an economic framework - is about government intervention that aids the economy in determining the level and direction of technological change. It is important for determining the dynamic and future nature of the economy, not just for the environment.

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10.1 Appendix: Modelling Growth with Environmental Preferences

In this Appendix we set out the basics for modelling resources within growth, with a focus on the role of natural resources in sustainable development. Following Smulders [2000], it is straightforward to set out the conditions establishing a Doomsday model, i.e. a model in which growth cannot be sustained. Let us assume that no production can occur if environmental quality falls short of a threshold level $\bar{N}$. When $N > \bar{N}$ output is a function of a fixed proportion of natural inputs P, reproducible capital K and exogenous technological capital T. In this model unbounded growth is not feasible. Because growth requires natural inputs and other inputs in fixed proportion, environmental quality eventually declines below $\bar{N}$. Reversing the logic, the model is informative regarding the first requirement for sustained growth: The substitutability between natural capital and reproducible capital.

Smulders [2000] analyses optimal environmental policy in the framework of a stylized model of exogenous growth. In his model, society can benefit through two channels from improved environmental quality. First, the agents benefit directly from improved environmental quality. Second, improved environmental quality feeds back into higher total factor productivity (e.g. reducing illness). Environmental quality N behaves as a renewable resource: $\dot{N} = E(N) - P$, where E refers to the capacity to absorb pollution P. Assume that $P = E(N)$, i.e. the economy is in a steady state. To improve environmental quality, P has to fall initially. Figure 10 illustrates the importance of the initial stock of natural resources. If the stock is relatively low, a temporary decrease in pollution may lead to a situation with higher environmental quality in which also a higher level of pollution can be sustained. This feature is driven by the increased absorption capacity $E(N)$ as long as $N < N_{msy}$. However, if environmental quality surpasses the maximum sustainable yield N_{msy}, then pollution has to be permanently reduced to sustain a higher level of environmental quality. The later, leads to a fall in productivity which can be offset by the second effect (increase in total factor productivity) if N is close enough to N_{msy} and the standard of living. Smulders [2000] derives a golden rule for environmental policy: $E_N N/E = -\chi/\omega$, consumption is maximized if the elasticity of the absorption function E with respect to environmental quality equals minus the ratio of the production elasticity of non-rival use of environment χ and the elasticity of production of rival use of the environment ω.

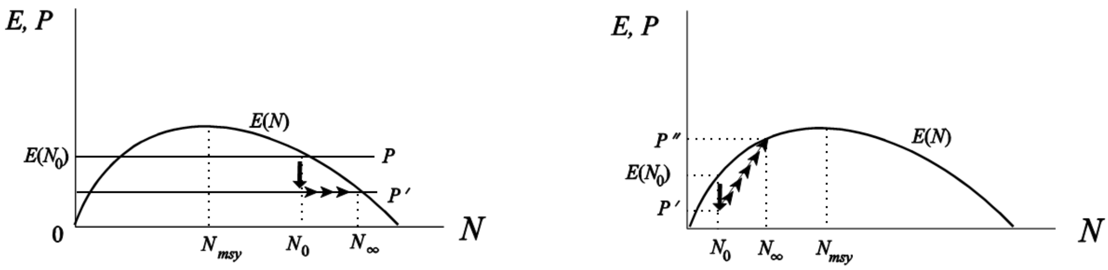

Figure 10: Environmental quality and absorption capacity, source: Smulders [2000]

However, the golden rule does not take into account neither intertemporal preferences nor the amenity value of the environment. It maximizes consumption in the long run but not utility. To correct for the later shortcoming, Smulders [2000] derives a green golden rule. The optimal savings rate is determined by $s = \beta$ as in the classical Solow growth model and optimal environmental policy is determined by: $\frac{E_N N}{E} = -\frac{\chi + \phi(1-\beta)}{\omega}$, where the amenity is parametrized as

ϕ. The green golden rule implies a more ambitious environmental policy for an infinitely altruistic society. The more society values the environment, the larger the optimal stock of natural capital and hence the more consumption is sacrificed for a cleaner environment. Interestingly, the model also implies the higher productivity of capital the lower the optimal investment in environmental quality (amenity), i.e. the opportunity cost of investing in environmental quality increases with the productivity of capital.

While the green golden rule includes societies valuation of the environment, it does not deal with the trade-off between short term costs and long term gains of environmental policy. Based on a dynamic optimization problem, Smulders [2000] derives a modified golden rule: $\beta Y/K = \delta + \vartheta + g/\sigma$, which implies the optimal savings rate $s^* = \frac{\beta(g+\delta)}{\delta+\vartheta+g/\sigma}$. The more impatient (high ϑ) and the more inflexible (i.e. inter temporal substitution is small σ) a society is, the smaller the optimal savings rate. The higher the returns to capital (higher β), the higher optimal savings. Equation 1 illustrates the trade-off between an investment in capital and in environmental quality:

$$\frac{\beta Y}{K} - \delta = \frac{\dot{\omega Y/P}}{\omega Y/P} + E_N + \frac{\chi + \phi C/Y}{\omega}\frac{P}{N} \tag{1}$$

A condition for optimal policy is that the net return to capital equals the return on environmental quality. The later carries value for society for four reasons: First, it absorbs wastes and provides resources. Second, improvements in environmental quality may lead to increased absorption capacity. Third, through the productivity effect of the environment (χ). Fourth, the environment is valued per se as an amenity (ϕ). Taken together with the Ramsey type equation, optimal policy is determined by:

$$\frac{E_N(N)N}{E(N)} = -\frac{\chi + \phi(1-s^*)}{\omega} + \frac{N}{E(N)}\left(\vartheta + \frac{1-\sigma}{\sigma}g\right) \tag{2}$$

Hence, in this model sustainability can be achieved but is not always optimal. If the discount rate ϑ is too high (i.e. a high value is placed on the short term costs of environmental policy) equation 2 may not hold. For sustainability to be desirable (optimal), society needs to be sufficiently patient, environmental quality has to substantially increase productivity and be valued as an amenity.

What does this model imply for growth and environmental quality? Growth affects optimal environmental quality through two channels: Technological progress makes capital and natural inputs more productive; therefore investment increases. At the same time, agents may want to smooth consumption by anticipating the productivity gains. Which effect eventually dominates depends on the rate of intertemporal substitution. Secondly, the opportunity cost of investment in environmental amenities increases due to increased productivity. Through this channel higher growth decreases environmental quality. In conclusion, the effect of growth on environmental quality is ambiguous if intertemporal substitution is high and negative otherwise.

Smulders [2000] extends his previously discussed framework by including endogenous technology. In this model, technological progress is entirely the result of investment in the stock of knowledge (e.g. R&D). Therefore, technological progress is determined by similar incentives and it also has similar effects as investments in the stock of capital. Constant returns are assumed with respect to man-made capital and the diminishing returns are offset by the interaction of investment in technology and capital.

As in the previous neoclassical growth model, capital K and output Y grow at the same rate in the long run. Also, the newly introduced technology capital H grows at this rate. The growth rate is endogenously determined in the model.

$$g_\infty = (s_K^\beta s_H^{1-\beta}) L^\alpha E(N_\infty)^\omega N_\infty^\chi - \delta \tag{3}$$

From equation 3, we can see that the long run growth rate depends on environmental quality through the environmental absorption capacity $E(N_\infty)$ and a direct productivity effect N_∞^χ. Smulders [2000] finds that environmental quality has a positive effect on growth if equation 4 holds.

$$\frac{E_N}{E} > -\frac{\chi}{\omega} \tag{4}$$

The maximum growth rate is pinned down by the optimal level of environmental quality as determined by the green golden rule. If the initial environmental quality is below the golden rule level, environmental policy can improve both environmental quality and growth. However, if the initial level is higher, further increases in environmental quality come at a cost.

To achieve the optimal growth rate, investment has to be made such that the rate of return on physical capital and technological capital are equalized. As previously, if more pollution is allowed, capital is more productive. Increased environmental quality directly feeds into the productivity of capital through its effect on total factor productivity.

Smulders [2000] finds that the long run growth rate is affected by environmental quality through the rate of return. He points out that "win-win" situations are possible. Investing in the environment means also investing in productivity. The absorption capacity of the environment may increase and environmental improvements have a direct productivity effect at the same time. In particular, if the initial level of environmental quality is lower then the level determined by the green golden rule, improvements in the environment and economic growth go hand in hand. Beyond this level, environmental improvements come at a cost for society: Productivity has to be sacrificed for the enjoyment of a higher level of environmental quality.