Technological Regimes, Environmental Performance and Innovation Systems: Tracing the Links

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1. Introduction

There has been a growth in academic and policy interest in the notion of systems-level technological changes (regime shifts, systems innovations) that promise to bring about radical improvements in environmental efficiency (cf. Frosch and Gallapoulos 1989; Vellinga et al 1998). Perhaps the clearest example is the debate about shifts to low-carbon energy economies as a way of mitigating climate change (Royal Commission 2000; Grübler et al 1999). This debate stems from three kinds of conviction: that current patterns of economic development are environmentally unsustainable; that these patterns of development are nevertheless deeply entrenched by technological, economic, institutional and cultural commitments; and that alternative technological and institutional configurations can be designed that will deliver both environmental and economic benefits over the longer term.

The notion of regime shifts raises a number of profound questions. Can regime shifts be induced or stimulated? Is it possible to have foresight about their outcomes (economically, socially and environmentally)? Are they governable, or do they possess some inherent and autonomous inertia? If regime shifts can be induced, foreseen and managed, then the problem for policy is to formulate and implement a strategy that will encourage the innovation of new and known technologies, and to create around these technologies institutional frameworks that will enable their broad and effective diffusion. With this characterisation of the problem in mind, a regime shift is a goal-oriented system innovation carried out at a large-scale. Almost by definition, such processes of innovation are unlikely to emerge from existing market conditions and relationships. An innovation policy would therefore be central to a regime shift.

However, if regime shifts cannot be induced, if their outcomes are uncertain, and if, where they occur, they are substantially autonomous in their dynamics, the set of policy prescriptions would be very different. Instead of formulating and implementing strategy, the aim would be to seek to adapt and adapt to emergent features of new technological and institutional forms as they unfold. That is, rather than moving along a planned route towards a predetermined destination, the aim would be to incrementally follow a path the direction of which is only vaguely known and which may be subject to revision. The debate about technological regime shifts therefore mirrors a much older debate about innovation and strategic management (compare the ‘rationalist’ school of Ansoff (1965) with the ‘emergent’ school of Mintzberg (1987)).

This paper is concerned with innovation and environmental performance in technological regimes. The aim is to understand how the full range of technical changes in large, integrated technological systems interact, and how they influence the shape of these systems’ environmental profiles. We also investigate the way in which expectations about future alternative trajectories of change may influence environmental profiles. We are concerned with two interlinked questions:

- How does technical change occur in technological regimes, and in particular, how far can ‘environmental’ factors be seen to have induced these changes? Where can we find evidence that ‘environmental’ pressures have had a significant impact on the rate and direction of technical change? And, following the arguments of some commentators, are these environmental pressures leading to a more preventive approach to environmental management?
- Is it possible to distinguish ex ante between more and less environmentally desirable trajectories of regime change? Can we employ technology foresight and environmental assessment techniques to describe a clear route of transition for technological regimes?

Drawing on what has been learnt from the combination of qualitative innovation studies and quantitative environmental assessment studies in two regimes (paper and PVC production), we describe a conceptual model that sets out the relationships between different forms of technical change and a range of economic and institutional factors that appear to determine them. We characterise innovation (and environmental performance) in technological regimes as unfolding dynamically out of the interaction of four types of innovation: abatement innovations; process innovations; product innovations; and infrastructural changes. Each of these forms of innovation link to distinct components of innovation systems and have distinct environmental outcomes. We argue that the opportunities and pressures for each form of innovation (and their interaction) are specific to the technological regime and sector. We conclude by reflecting on what might be termed the ‘paradox of commitment’ (Walker 2000). This is the observation that in order for innovation to take place there is a need for some degree of technological, economic and institutional commitment, but that at the level of the technological regime (as at lower levels of the system) the outcomes of such commitments are emergent and highly uncertain.

2. Framing Environment-Innovation Studies

Innovation studies concerned with the environment are interested in capturing environmentally relevant changes in technology, institutions and the behaviour of market actors. A previous generation of environment-innovation studies were primarily interested in the generation and diffusion of specific ‘environmental technologies'. Skea (1995) provides a typical classification of environmental technologies (table 1). For these studies the appropriate frame of analysis was the technological artefact and the management procedure. For these studies the critical problem was to understand how to induce change in these artefacts and procedures. The empirical evidence shows that pressures that induce these types of change come from many sources, including regulators, customers and management routines within the firm (Irwin and Vergragt 1989; Dorfman et al 1992; Groenewegen and Vergragt 1991; Jackson 1993). Few generalisations emerged from this work. To a large extent the neo-classical literature on innovation and the environment has retained this focus on discrete techniques and their innovation and diffusion (cf. Jaffe et al. 2000; Ruttan 2000). Analysis tends to stress the importance of price as an efficient means to induce the innovation and diffusion of specific techniques and processes.

Table 1. Categories of Environmental Technology

Class of technology	Definition
Pollution control	pollution abatement; effluent removal (classic end of pipe techniques)
Waste management	handling, treatment and disposal of wastes
Recycling	waste minimisation through reuse of materials recovered from waste streams
Waste minimisation	production processes and techniques to minimise waste
Clean technology	production processes that give rise to low levels of environmental impact
Measurement and monitoring	sampling, measurement and data analysis
Clean products	products that give rise to low levels of environmental impact through their life cycles

Skea 1995

The environmental technology literature has tended to stress the distinction between abatement (end of pipe) technology, and 'clean' technology (typically seen as novel process innovations). A strong and highly influential argument for a more *preventive* approach to environmental management builds on this distinction[1]. According to this argument, the prevention of waste and emissions is preferable, from an environmental and an economic perspective, to their abatement. By reformulating products, changing inputs and operating production processes, it is possible to avoid the generation of wastes, so avoiding the need for investments in abatement technology. Emphasis is therefore placed on the need for process and product innovation that is oriented at eliminating waste and reducing emissions. If this form of innovation can be induced, or if it is motivated by the competitive advantage that may be gained through associated cost savings, so goes the argument,

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[1] The 1996 EC integrated pollution prevention and control directive (IPPC) regime can be seen as a direct policy response to this 'preventive' approach to environmental management.

environmentally-driven process innovations will substitute for innovation in abatement technologies.

The final expression of this position suggests that innovation in environmental technologies will follow a number of phases, recalling earlier 'stages models' of environmental management (cf. Hunt and Auster 1990; Roome 1992). These phases of innovation will be defined by the interplay of regulation, growing innovative capabilities in industry, and more sharply defined incentives in the market (cf. ACOST 1992). In the first phase, starting from a basis of low environmental pressure and low technical capabilities amongst technology suppliers, the primary response of industry to environmental problems is well-established end-of-pipe controls (electrostatic precipitators in cooling towers, for instance). In a second phase, with growing environmental pressure and a greater emphasis on waste reduction and management, specialist suppliers of abatement technology emerge and suppliers of process technologies also begin to compete on environmental performance. In a third phase, integrated, strong environmental pressures from regulation and the market lead to preventive approaches to environmental management becoming a key focus of innovation amongst capital goods suppliers and the market for abatement technologies declines. A clear path from reactive to preventive management approaches enabled by a transition from end of pipe to 'clean' technology is laid out in this 'model' of environmental technology innovation.

While intuitively appealing, there are a number of limitations to this framing of environment-innovation analysis. First, a focus on atomised, micro-level changes in technology is liable to miss dynamics across the wider technological system that may be more significant. For instance, the substitution of a cleaner way of synthesising chlorine may be less significant than the rise in overall efficiency through the growth in the scale of production. Second, studies are faced with the non-trivial definitional problem of distinguishing between a 'clean' and a 'dirty' technology. The definition usually appears to rest on claims made by technology suppliers about how much environmental 'effort' went into the design and configuration of a new technology. What sets an environmental technology apart is therefore the strength of the regulatory or other pressure that can be claimed to have influenced its development, rather than an objective measure of its environmental performance. Where environmental outcomes are measured, a single dimension of performance is typically highlighted (SO_2 abatement in flue gas desulpurisation equipment, for instance). Little account is taken of the broader systems impacts that a new 'clean' technology may have. Indeed, a common feature of early environment-innovation studies was their lack of attention to the quantification of environmental performance. Third, the emphasis on discrete technologies, leads to a focus on new investment and substitution of one technology for another, and a lack of attention to processes of incremental innovation. In many technological systems incremental change is extremely significant, especially since capital turn-over rates are slow. To give an example from one of the case studies discussed later, a survey in 1997/98 of paper machines in the EU revealed that their median age (not accounting for rebuilds) was 32 years (Berkhout et al. 2000). But this slow rate of substitution did not mean that production processes were static, or that their environmental performance remained unchanged.

Numerous small adjustments and adaptations are made to industrial processes which, over time, have a significant influence on the environmental performance of a plant and an industry.

In response to these problems, more recent environment-innovation studies have broadened the scope of analysis. In the 'ecological modernisation' literature, which has emphasised the importance of technological innovation in reconciling economic development with ecological sustainability, there has been a demand for 'meso-level' explanations. In particular, there has been a drive to include institutional contexts and processes into the picture, arguing that the correct focus should be on the co-evolution of technical and institutional innovations (for recent reviews, Mol and Sonnenfeld 2000; Murphy 2000; Anderson and Massa 2000; Saviotti 2003 in this volume).

In more technically-informed 'industrial ecology' literature there has likewise been a shift towards 'systems studies' that aim to understand the resource and environmental profiles of technological systems in the round, typically along supply chains from cradle to grave (Socolow et al. 1994; Graedel and Allenby 1995; Ayres and Ayres 1996). This may be seen as an attempt at an analysis of the co-evolution of environmental systems (services and sinks) and industrial systems - the aim being to understand the total environmental consequences of a given product or service delivered through technological activities. A series of more normative objectives for technological transformation have emerged from this work, with a vision being painted of highly cyclical, solar-powered industrial systems achieved over the longer term.

The more recent concern with systems innovations and technological regime shifts can be seen as emerging from this intellectual context (Kemp et al. 1998). This institutionalist analysis of technical change is concerned with linking between several levels of change - micro-, meso- and the macro - what Geels (2002) term niches, regimes and socio-technical landscapes. Again, the stress is on the co-evolution of technical and institutional systems, the primary difference being goal-orientation. Here clear socio-technical goals are defined through a process of deliberation and systems innovation is managed by integrating adjustments and changes across multiple levels.

3. Change in Technological Regimes

The greater emphasis on technological regimes has changed the terms of the analysis of environment and innovation. The nature, rate and direction of change in a technological regime differs from change in discrete technological artefacts. Regimes are composed of stable assemblages of technical artefacts, organised in co-evolving market and regulatory frameworks. Because of the inter-related and interlocking nature of technological regimes, change is both slower and may be seen as following more predictable trajectories. For a regime change to occur it must be recognised as necessary, feasible and advantageous by a broader range of actors and institutions than would be the case for a discrete technological change.

In general, analysis of change in regimes has therefore tended to emphasise stability and continuity, seeking to explain why competing technological regimes only rarely emerge.

A range of explanations for these processes of technological channelling, path dependence, 'lock in' and 'lock out' have been proposed. Dosi (1988), using the term 'technological paradigm', argued that technological regimes were defined as '...a pattern for solution of selected techno-economic problems based on highly selected principles…'. In this analysis the choice of technical problems is defined by prevailing knowledge and problem-solving heurstics that '…restrict the actual combinations in a notional characteristics space to a certain number of prototypical bundles.' Arthur (1989) argued that learning effects and increasing returns to economic scale would lead to a process of technological 'lock in' that would systematically exclude competing and possibly superior technologies. David (1985) in his famous, though controversial, example of the QWERTY keyboard argued for three factors leading to path dependency in technological change: technical interrelatedness; economies of scale; and quasi-irreversibility. The first and the last of these relate to the 'switching costs' involved in moving from one technological regime to another (Berkhout 2002). A number of other well-known studies use different cases to make similar arguments (Cowan and Gunby 1996; Islas 1997; Leibowitz and Margolis 1999). Finally, Walker (2000) in analysing the persistence of nuclear reprocessing technology in the UK stresses the importance of embedded institutional, political and economic commitments to a particular technological regime identified with a long-term need. He argues that this process of institutional 'entrapment' is ubiquitous in large technical systems where infrastructures contain large and lumpy blocks of capital. Without heavy commitments by key interests defection would be too easy and technological regimes too fragile to develop.

In sum, the literature on change in technological regimes places emphasis on persistence of change along well-defined pathways because the generation of novelty is bounded by working assumptions and procedures inherent to that regime, or because there are a range of institutional and technical barriers to switching away from one regime to another (Berkhout 2002). In the following section, the links between innovation and environmental performance in two technological regimes will be analysed and compared.

4. Innovation and Environmental Performance in two Technological Regimes

The manufacture of two products – rigid polyvinylchloride (PVC) used in construction and coated printing and writing papers – was analysed and compared using a common methodology[2]. These two materials were chosen because they represent commodities that had remained relatively stable over a significant period, so permitting a longitudinal study of innovation and environmental performance.

Two sets of analysis were carried out. The first analysis aimed at understanding innovation and technology dynamics within each sector, disaggregated into major process steps (for example, forestry, pulping, paper milling, paper recovery, deinking and fibre recycling for the paper sector). These studies focused on changes in technology and productivity, but also dealt with changes in industrial organisation, the strategies of firms organised across production systems, and relationships between technology suppliers and users. The second set of analysis used life cycle analysis (LCA), covering identical production systems, to explore the system-wide environmental effects of infrastructural, process, product and abatement innovations that had been documented in the innovation studies. Life cycle models segment production systems into stages that were analysed in the context of the whole technological system. No *a priori* distinctions were made between innovations judged to be 'environmental' and those that were not – all relevant technical changes were included in the analysis[3]. The study took a dynamic perspective with both a 'back-casting' historical review of trends in innovation and environmental performance, and a forward-looking scenario-based analysis of alternative portfolios of technical change. The time-frame for the study was 1980-2010, using 1995 as a base year. The two case studies were carried out in parallel according to a common research design. A matching level of analysis was adopted for the study of innovation and environmental performance in these technological regimes so that the innovation studies and the environmental assessments were tightly coupled. An analysis of the impacts on competitiveness of each of the identified innovations was also carried out, but this is not discussed here.

4.1 The Innovation Studies

The innovation studies had two objectives. First, to establish the drivers, sources, rates and direction of technical and organisational changes in production processes. 'Backcasting' over the period 1980-95 was designed to provide an under-

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[2] These case studies are drawn from the Sustainability, Competitiveness and Technical Change study (1997-2000) funded under the EC's F4 Environment and Climate Programme. The study was coordinated at SPRU, University of Sussex, and partners included the Department of Economics, Technical University of Berlin, and the Institutet for Vatten- och Luftvardsforskning (IVL), Stockholm and Gothenberg.

[3] 'Incremental' and 'radical' innovations were included, although no attempt was made to classify innovations according to these categories.

standing of underlying technological and industrial dynamics in the two sectors. Second, the studies aimed to develop futures scenarios for production processes (archetypal process routes) to serve as the basis for environmental and policy analysis. Forecasting covered the period 1995 to the 2010s. Four alternative scenarios were elaborated in both the case studies (dynamics as usual, recovery and recycle, eco-efficiency, and pollution prevention, see below). Different sets of technological options were bundled to reflect the specific objectives of each scenario allowing alternative models of process routes to be built up. The main sources of evidence for the innovation studies were primary and secondary literature, and interviews with technologists and researchers in the paper and chemicals industries[4].

4.2 Life Cycle Analysis Models of Environmental Performance

A formal modelling approach was taken to environmental performance assessment. Models of 'archetypal' process routes were developed for both case studies on the basis of existing LCA software (KCL). These model process routes were taken to be representative of EU production systems in the two sectors. Slightly different approaches were taken to model construction and selection of parameter values in the two cases. For the paper case, existing KCL data (developed by a Finnish forest industries research organisation) was modified using new data from Swedish, Finnish and German pulp and paper mills. For the PVC case, no mature and parameterised LCA model was available, and a new model was constructed on the basis of data from a single Swedish facility. This data was compared with data available in the literature from other plants, and modified where appropriate to improve its representativeness and consistency.

In choosing parameter values, a balance had to be struck between the competing considerations of representativeness, policy relevance and data availability. A *hybrid* approach was adopted. For background modules (primarily of energy and electricity production) EU-averages were used. For foreground data (those relating to the production processes themselves), the aim was to use information from existing validated databases and plants that would represent 'good' productivity and environmental performance. Parameters chosen were peer reviewed by industry experts throughout the model development process.

The life cycle inventory models were used as research tools to investigate the environmental impact of technical and structural changes in the two industries. For the PVC case, six model configurations were developed: benchmark processes for 1980 and 1995, and four alternative scenarios for 2010. For the paper case, eleven configurations were generated, including the six listed above. Five additional runs were conducted to take account of different energy and fibre contexts in Scandinavia and west-central Europe.

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[4] In all some 150 interviews were conducted in the period 1997/98.

4.3 The Technology Scenarios

Scenario analysis is a well-established approach for dealing with uncertainty about the future (cf. Ringland 1998). Scenarios were used in the study as a way of providing clear principles for identifying technical changes that might be expected under different future policy contexts. In order to make claims about the impacts on environmental performance and competitiveness of alternative trajectories of technological and organisational change, it was necessary to begin with a 'dynamics as usual' scenario. Under this scenario, a common approach was taken by using existing Best Available Technology (BAT) standards for 2010. In the paper industry case this was defined in recently published IPPC Best Available Technology Reference (BREF) note. In the PVC case these were derived from definitions provided by the European trade association EUROCHLOR in support of the BREF Note, and from specifications produced under OSPARCOM[5].

In each of the three alternative scenarios (eco-efficiency, pollution prevention, recovery and recycling), the aim was to test the technological and environmental implications of pursuing different policy goals. A wide-ranging technology foresight exercise was undertaken. This generated inventories of innovations for each of the major process steps for both paper and PVC. The scenarios were framed by assuming specific technology choices (represented as specific parameter values in the LCA models) that matched a given policy objective, with other objectives given less prominence. Bundles of technologies were clustered according to how appropriate they appeared to address a specific policy goal. The scenarios chosen met three basic criteria: 1) they were applicable across the two case studies; 2) they illuminated current policy choices and 3) they pointed up theoretical debates about the relationship between technical change and environmental performance. The three scenarios were characterised as follows:

1. Eco-Efficiency: Maximising resource productivity was a key goal of technological changes in this scenario. Inputs of materials and energy were assumed to be minimised, regardless of the impacts on emissions and on recycling (in fact, recycling is often consistent with resource productivity). This involved process changes, as well as changed assumptions about the composition of final products.
2. Pollution Prevention: Minimisation of emissions to the environment was the main goal of technological changes modelled in this scenario. Some process changes and full adoption of available abatement techniques were included under this scenario. Input and product composition were retained from the baseline scenario.
3. Recovery and Recycling: Maximum reuse of materials and energy resources was the key goal under this scenario. The main focus was on post-consumer wastes, in-process recovery and recycling being integrated into the eco-efficiency scenario.

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[5] The Oslo and Paris Commissions under which marine pollution in the NE Atlantic is regulated.

4.4. Technological and Market Characteristics of the Two Sectors

4.4.1 Polyvinyl Chloride

Polyvinyl chloride is probably one of the oldest polymers in modern use. Regnault in France first produced vinyl chloride monomer in 1835 and Baumann first recorded its polymerisation in 1872 when he exposed sealed tubes containing the monomer to sunlight. The earliest patents for PVC production were taken out in the USA in 1912, and pilot plant production of PVC began in Germany and the USA in the early 1930's. A production site was first started in Schkopau in 1938.

PVC is a chlorinated hydrocarbon polymer. In contrast to many other plastics, it is not exclusively based on crude oil/natural gas resources, but contains a considerable amount of chlorine produced by chlor-alkali electrolysis of rock salt or brine. However, while PVC uses less oil, the production and use of chlorine causes a number of environmental burdens. An early draw-back of PVC was its tendency to de-hydrochlorinate at higher temperatures. Not until the discovery of suitable stabilisers could processing technology advance to the point where the full potential of polymer could be realised. Today, by choosing suitable stabilisers and plasticisers, the polymer can be converted into a wide variety of different products. Some of these additives, principally plasticisers (phthalates) and stabilisers (often based on heavy metals like cadmium or lead) may cause environmental burdens during the production and conversion of PVC. Problems may also arise during use phase of PVC and during waste management. The incineration of PVC wastes causes additional environmental hazards, including the generation of dioxin and hydrogen chloride (HCl) during the incineration of PVC containing waste.

PVC production follows a standard production route. Hydrocarbon feedstock is converted by cracking to ethylene (ethene). Sodium chloride is electrolysed as an aqueous solution to produce chlorine with sodium hydroxide and hydrogen as co-products in a process known as *chlor-alkali electrolysis*. The ethylene and chlorine are then reacted to produce 1,2-dichloroethane (ethylene dichloride, EDC) in a process called *direct chlorination* (DC). The EDC is then decomposed by heating in a high temperature furnace (cracking) to produce vinyl chloride and hydrogen chloride in a process called *pyrolysis*. If the process were stopped at this stage, 50% of the input of chlorine would be lost from the system, representing a significant loss of raw materials. In practice, the hydrogen chloride is reacted with further ethylene in the presence of oxygen to produce more EDC in a process called *oxy-chlorination* (oxy). The EDC produced by oxy-chlorination is also decomposed by pyrolysis.

PVC resin can be made by three different processes: suspension, emulsion and bulk (mass) polymerisation. The resins obtained from these processes possess somewhat different physical properties and are generally used in different applications. Suspension PVC (S-PVC) is general-purpose grade and is used for most rigid PVC applications such as pipes, profiles and other building materials. It is also used for most flexible applications such as cable isolation, foils, and various products made by injection moulding. Emulsion PVC (E-PVC) is primarily used for coating applications such as PVC coated fabrics. Bulk or mass PVC (M-PVC) is used for specific types of hard sheets and bottles. Finally, the PVC resin is compounded with different additives (related to the final application) and converted by different processes to the desired application.

Production of PVC is highly concentrated in a few global chemical companies, although the degree of vertical integration varies. Producers of PVC do not all carry out the complete sequence of operations; some buy commodities such as sodium chloride, chlorine, hydrogen chloride, ethylene dichloride (EDC) and even vinyl chloride monomer on the open market and operate only the later stages of the process. Some PVC producers are also engaged in PVC compounding and manufacturing of PVC product.

4.4.2 Paper

Early European manufacture of paper (15th century onwards) was based on non-wood fibres, such as hemp, flax, linen and cotton rags. Industrialisation in the 19th century amplified demand for a non-seasonal raw material, and wood fibres became the dominant raw material for European paper production. First, wood is processed so that the fibre raw material is separated out or *defibrated.* This 'pulp' is then mixed into a water suspension which is sprayed onto a 'wire' conveyor belt, such that the water drains away to leave a 'web' of interconnected fibres. This web is squeezed between rollers and dried so that yet more of the water is removed to leave the final paper product: a web of cellulose fibres. Following use, the paper can be recovered, the fibres separated and cleaned, after which they can be re-used. Modern paper machines are improved derivatives of the first fourdrinier machine built by Donkin in 1807.

In practice, the industrial production of paper and board is complex and highly capital-intensive. Although the main raw material is wood, there are competing process options along the route from wood to paper. Different pulping technologies exist (mechanical and chemical). The fibre suspension which enters the paper making machine can be modified with additives and chemicals, and can be made up from a mixture of different pulp types. The pulp can be bleached by various methods in order to improve brightness of the final paper product. Apart from wood (or non-wood) fibres, paper may contain 'fillers' (kaolin and calcium carbonate) and colours. Fillers are used as a cheaper substitute for fibre and to impart opacity to the paper. Once the base paper has been produced, it may be coated or polished (calendering).

Post-use there are alternative techniques for de-inking fibres in commercial operation (calendaring). The precise mix of raw materials and processes chosen will determine the type and quality of the paper being produced (the main paper grades are: graphic paper; sanitary and household paper; packaging; and others (from cigarette paper to roofing materials)). Even within a given paper grade there is considerable flexibility in the configuration of pulp types and process options which may be available. Figure 1 is a schematic of the main process steps in the paper life cycle.

The structure of paper and board production follows two distinct patterns: integrated or non-integrated. In integrated production, pulp and paper and board production are co-located, usually near to forest resources. This structure is evident in Scandinavian paper production. Pulp production based on virgin fibre may also be separated from paper production that is located closer to final markets for paper. Most commonly, in this non-integrated structure mechanical pulp production remains co-located with paper making, while 'market' chemical pulp is purchased from other producers. Non-integrated mills are more typical in the central and southern EU. Proximity to markets also tends to improve the potential for using recycled fibres. De-inking plants are typically co-located with paper production.

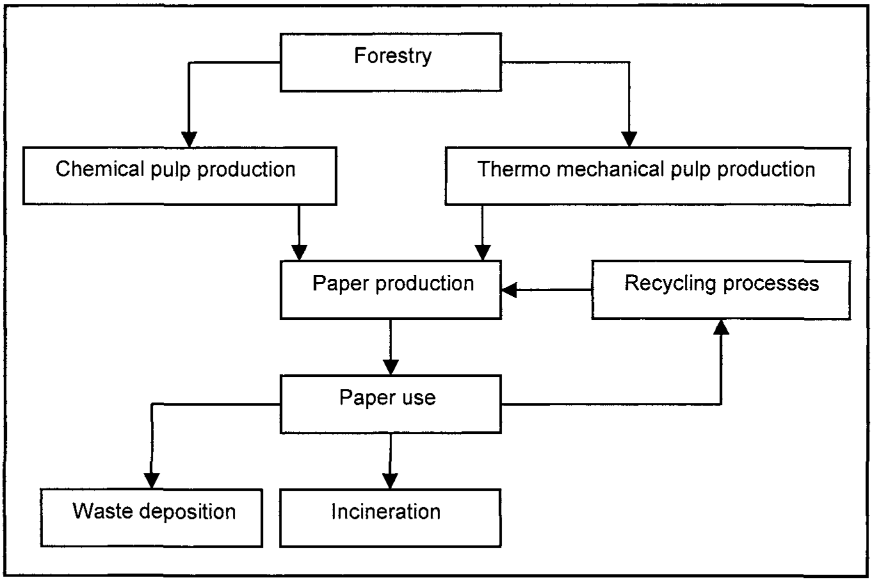

Fig. 1. Schematic of Paper Production System

4.5 Dynamics of Innovation and Environmental Performance: Principal Findings

In describing and analysing the co-evolution of technological innovation and environmental performance in two mature process industries, we were interested in two questions, both related to the question of technological transitions under the influence of 'environmental' pressures. First, we were interested in whether we could find evidence of a transition in the pattern of innovation from 'end of pipe' to clean technology (novel process innovation) as predicted by 'stages' models of environmental technology. Second, we were interested, using scenario analysis, in whether it was possible to distinguish between the environmental performance of alternative bundles of existing or forecast technologies grouped together in pursuit

of alternative policy goals: eco-efficiency; waste minimisation and recycling. As explained, these alternative process routes were designed to respond to prevailing policy debates, but they also serve as a more generic ‘thought experiment’ to test the assertion that it is possible to define an ‘end state’ towards which alternative (more sustainable) trajectories of technological change may be directed. The discussion of results of the study is organised under a series of six synthetic headings.
Innovation in mature industries takes many forms: The pulp and paper and PVC case studies demonstrate that a wide range of inter-related technological changes occur continuously and in parallel within mature process industries. Most of these are incremental and cumulative changes made to processes, although there are clear gradations between different forms of process change. Some involve more radical changes – the development of commercial-scale de-inking in the paper sector, for instance – while others are more limited procedural changes. Table 2 provides a categorisation of different forms of process change, including an assessment of the types of knowledge required for firms to carry them out. Clearly, the more profound the change, the more costly and risky it will become for producers, and the less frequently they will be made. Some more radical and novel process changes may be avoided by some producers altogether.

But process changes alone do not tell the whole story. The study showed that to a varying extent, product innovation continues to be an important factor in mature price-competitive industries. These product changes involve both quality improvements (better strength and printability characteristics for paper), as well as more significant reformulations that force process changes. A good example here is the demand for elemental chlorine-free paper in the early 1990s that required a new bleaching process to be adopted and a whole set of other incremental adjustments along the production process. Product innovation is generic and continuous, rather than rare and discontinuous. In both sectors a complex and dynamic interaction between innovation in products and processes is observed, with multiple and location-specific changes being made. The prediction of a decline in product innovation made in the classical Abernathy-Utterback model is therefore not confirmed (Abernathy and Utterback 1978).

Table 2. Categories of Process-based Innovation[6]

Category	Knowledge/Vintage	Example
Radically novel	New and comprehensive/total replacement	De-inking technology (paper)
Novel A	Substantial advance/modular replacement	Elemental chlorine-free bleaching (pulp), membrane technology (PVC)
Novel B	Substantial advance/rebuild, retrofit or re-design	Instrumentation and digital control systems (PVC and paper)
Incremental A	Minor advance/replacement	Upscaling of paper machines (paper)
Incremental B	Existing or minor advance/rebuild, retrofit or redesign	Fibre stock recirculation (pulp), system integration (paper)
Incremental C	Existing or minor advance/continuous	New materials in naphtha furnace (PVC)
Incremental D	Procedural or organisational	Environmental management systems

Two further sources of innovation were also highly influential for environmental performance. First, the development of progressively more efficient abatement technologies, and second the background development of energy infrastructures. In energy-intensive industries the configuration of the electricity grid has a profound influence on the overall environmental performance of the final product. As these electricity infrastructures are modernised and periodically transformed through the introduction of new technologies (the rapid diffusion of gas-fired power stations in the UK in the 1990s, for instance), so the environmental profile of products in the whole economy can also be reshaped.

Environmental performance of production systems is influenced by a mix of technological changes. The prevailing conceptual framework of environmental change in industry is a 'pressure-response' model - environmental pressures (whether regulatory or market-driven) influence firms leading to changes in technological choices and management routines. These, in turn, lead to relative improvements in environmental performance. Systematic modelling of two production systems and their environmental impacts has shown that technological changes underpinning changes in environmental performance frequently are not shaped by environmental factors. While there are cases (investments in abatement or novel chlorine-producing processes, for instance) where environmental factors are clearly dominant, there are a range of technological changes with major environmental performance impacts that are motivated by cost-saving or quality changes. Attempts to segregate those changes that are environmentally-driven from those that are not in the manner implied by the pressure-response model is both theoretically and empirically unjustified. All innovation, no matter what the factors shaping it are, must be considered as having potentially positive or nega-

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[6] Adapted from M. Bell, 'Cleaner Technology: Where does it come from?', SPRU, University of Sussex, March 2000.

tive environmental impacts. There is a need to consider the relationship between innovation and environment in a more integrated way, beginning with an analysis of innovation, rather than with an attempt to isolate 'environmental' or 'clean' technological changes *ex ante*.

Tables 3 and 4 show that, seen from the perspective of the technological system, the key changes underlying the dynamics of environmental performance include investments in abatement, process change, product changes and changes in the background energy mix. Some of these changes were made with environmental performance being a consideration, while many others were not. The results show that the 'green lens' often applied by analysts of the relationship between innovation and environment is unhelpful. By integrating innovation studies with life cycle analysis, methods now exist for moving beyond this framing of the problem.

Table 3. Technology Changes Underlying Environmental Performance Dynamics: Pulp and Paper Production, 1980-95

Indicator	Key technology drivers of environmental performance change
CO2	Background energy mix change
Timber use	Product change (higher filler and recycled fibre content in paper), Process change (fibre stock recirculation)
NOX	Engine efficiency (transport), process change (higher energy efficiency in pulping), background energy mix change
SO2	Sulphur dioxide abatement (pulping)
BOD	Abatement (waste water treatment), process change (heat recovery from organic pulping wastes in mechanical pulp), product reformulation (higher recycled fibre use)
COD	Waste water treatment
AOX	Process change (elemental chlorine-free bleaching)

Table 4. Technology Changes Underlying Environmental Performance Dynamics: PVC Production, 1980-95

Indicator	Key technology drivers of environmental performance change
CO2	Background energy mix, process change (VCM production)
NOX	Process change (naphtha production), abatement
SO2	Sulphur dioxide abatement (low sulphur fuels)
Dioxin	Process change (polymerisation)
Chlorinated hydrocarbons	Process change (closed reactor polymerisation)
Hydrogen chloride	Waste management (on-site incineration of chlorinated VCM wastes)
Mercury	Process change (phase-out of mercury cells in chlorine production)
Cadmium (air)	Product reformulation (phase-out of cadmium stabilisers)
Lead (air)	Product reformulation (introduction of lead stabilisers)

If it is not possible to attach an environmental 'flag' to innovations leading to changes in environmental performance, then the 'environmental pressures-technological response' model proves inadequate. This poses both a theoretical and a policy challenge. The theoretical challenge is to develop a better model. The policy challenge stems from the recognition that even apparently direct instruments like technology-based emission standards are only part of what lies behind the reshaping of the environmental profiles of industries. Other policies, influencing industrial structures and the general technological performance in firms also play a significant role.

Novel process technologies (clean technologies) do not play a dominant role in defining the environmental profile of production systems. The 'clean technology' model implies that, through time, technological opportunities for pollution abatement will decline. In this account, and assuming a constant level of 'environmental' pressure, we would expect to find evidence of a falling significance of investments in abatement and a growth in significant process innovations. In other words, we would expect to find a transition from a focus on abatement innovations towards process innovations.

The study tracked technological changes over 15 years (between one and two investment cycles in both the paper and integrated chemicals sectors). We did not observe a transition in the nature of innovation from abatement to process innovation, even though process-based industries represent a good case for such a transition. Moreover, we found no evidence that opportunities in abatement are being exhausted. New abatement techniques and continuous incremental changes in existing technologies are likely to play a significant role in changing industrial environmental performance in the future, in tandem with process and product changes. Novel process changes do occur: chlorine-free bleaching of Kraft pulp; and new chlor-alkali electrolysis technologies in vinyl production are clear examples. It is also clear that environmental pressures can be the principal drivers of these more profound technological changes. Nevertheless, the fundamental economic constraints on the introduction of novelty remain and this suggests that there is unlikely to be an acceleration of this type of innovation, except in cases where a sudden technological breakthrough is achieved, or a powerful exogenous shock is applied to the industry which brings to market viability new technologies that are currently uneconomic or not viewed as being mature.

Another aspect of novel process innovations is that they appear to provide very specific environmental benefits. Chlorine-related emissions may have been radically reduced through the introduction of new bleaching and electrolysis techniques, but they appear to have had little impact on other dimensions of environmental performance. Integrated environmental performance improvements appear to be achieved through more continuous, incremental technical change. Novelty therefore needs to be seen in the context of incremental change when considering the complete environmental profile of a technological regime. Encouraging novel or radical technologies may be at the expense of broader gains through smaller steps. These results suggest that a more balanced picture needs to be drawn in which all forms of technological change continue to play an often mutually-reinforcing role in achieving environmental performance improvements.

In mature process industries, improved resource productivity lies at the heart of competitiveness. The argument that there can be a correlation between improved environmental performance and competitiveness (the 'Porter hypothesis') rests primarily on the assertion that greater resource productivity brings appropriable economic benefits to producers primarily through lower input and waste management costs. This position suggests that by accelerating the rate at which resource productivity improvements are achieved by, for instance, introducing more novel resource-saving techniques, producers will be able to achieve greater competitive advantage.

While the basic premise of the argument is certainly correct, the inference that there are generally available opportunities for increasing the rate at which innovations leading to improved resource productivity are introduced does not appear to be supported by the evidence. Resource productivity is already a major focus for innovative activity in resource-intensive industries. The scaling-up of production capacity (the growth of paper machines, increased throughput in naphtha crackers and so on) and the adoption of yield and efficiency improving techniques are central to the normal technological activity of all producer firms.

The rate at which these changes are made is determined by the availability of new technologies from suppliers, the length of investment cycles, and the balancing of risk with expected returns from new investments. Although there are different technology strategies available to firms (some choosing a more risky, innovative strategy and others taking a more secure follower strategy), the increments in resource productivity that can be achieved at any time tend to be limited and predictable. This is borne out in the rates of change in some key input parameters for the PVC life cycle, as shown in Table 5.

Table 5. Annualised Rates of Change of Resource Productivity: PVC Production

Time period	Energy	Crude oil	Rock salt
1980-1995	2.07%	0.23%	-2.08%
1995-2010	1.09%	0.15%	-1.67%

Note: Positive rates of change signify improvements in resource productivity over time, negative rates signify declines.

Table 5 also shows another general trend highlighted in the study - the *declining rate* of resource productivity and environmental improvement in PVC production. From our analysis, the rate of environmental performance change in the 1980-95 period will generally not be repeated in the following 15 years, although there are exceptions.

Another illustration of this is expressed in Figure 2 which shows rates of change across key parameters of environmental performance for paper production in Scandinavia for the 1980-95 and 1995-2010 periods. In these models we have used 'base case' assumptions about technology. Only electricity consumption shows a more rapid improvement in the later period. Interestingly, the much higher rates of recycling assumed for the 1995-2010 period do not produce a 'step jump' in fibre use (timber), as might have been expected. Rather, these apparently radical changes (increased paper recovery and de-inking) driven by environmental pressures have merely enabled historical rates of improvement of environmental performance to be maintained.

Another complicating factor is the significance of product innovation. Technologically, producers are facing two options. They can search for ways of saving costs, but they can also search for ways of meeting the market demand for higher quality products. Growing competition, related technological developments (such as those in printing) and changes in market demand have forced producers to become more focused on product quality *and* product innovation. These product innovations can be at the expense of resource productivity, as clearly illustrated in the paper sector.

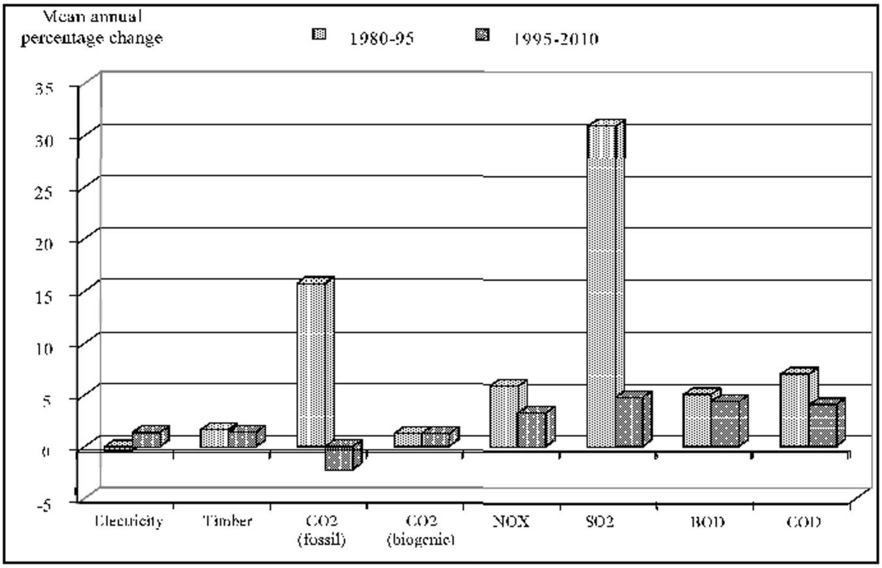

Fig. 2. Environmental Performance Change (Pulp and Paper): Scandinavia 1980-95 and 1995-2010

The results of the study therefore do not support the contention that more rapid improvements in resource productivity are available to firms through the introduction of novel resource-saving technologies. In process industries operating within rather inflexible technological trajectories, and where resource productivity and competitiveness are already strongly aligned, the scope for introducing radically novel resource-saving techniques may be limited. On the other hand, where novel processes have been introduced, the stimulus has frequently been ‘environmental’ (de-inking and chlorine-free bleaching in paper, and new electrolysis processes in

PVC). Product innovation has become a growing focus for these industries, and may have countervailing effects on resource productivity.[7]

The 'clean technology paradigm' is not borne out in this study: we can identify four 'stylised facts' in the clean technology literature: a) The notion that novel, discreet and identifiable industrial processes – 'cleaner technologies' – will bring step-jump improvements in environmental performance of industries; b) The idea that there will be a *transition* from innovations based on abatement towards innovations based on process change in the search for better environmental performance; c) The assumption that the introduction of novel techniques have a more marked impact on environmental performance than incremental change over time; and d) The argument that accelerated adoption of these novel clean technologies will bring competitive advantage to early movers.

Each of these stylised facts has been considered in the analysis and found to be only partially in accord with the empirical findings. First, on the question of the *identity* of clean technology, there are examples of novel technologies adopted under environmental pressures and with a marked impact on specific dimensions of environmental performance. But these are rare exceptions in a process of technological change that is multifaceted and often incremental. By placing too much emphasis on only one form of technical change, analysts and policymakers risk ignoring other powerful drivers of environmental performance change in industry. Second, we have been unable to find evidence of a *transition* away from abatement and towards novel process changes as a way of achieving environmental performance improvement. While process change is a significant driver of environmental performance change in industry, the reasons for this are not 'environmental' but connected to resource, cost-saving and product innovations. Abatement continues to be an important way for process industries to achieve improved environmental performance *at the same time*. The often-cited dichotomy between 'end of pipe' and process change therefore appears to be false.

Third, there is little evidence that process change really generates more rapid improvements in environmental performance than abatement. Indeed, we find that within dominant technological trajectories (as is the case in the pulp and paper and PVC sectors) process change tends to be rather slow and predictable, and that this will be mirrored in the rates of improvement in resource productivity and pollution burdens. By contrast, the development of new abatement technology can dramatically and rapidly alter certain aspects of the environmental signature of an industry. Lastly, while it is clear that resource productivity is a key factor in the competitiveness of mature process industries, it appears that opportunities to seek competitive advantage through the adoption of novel process technologies leading to environmental performance improvements may be limited. Fundamental uncertainties about the economic benefits of adopting more novel techniques will tend to constrain their diffusion.

Distinguishing between the environmental performance of alternative future technological pathways is difficult: a basic objective of the study was to seek to

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[7] Stronger, more opaque fibres required for lighter grades of paper require more refining of wood fibres in mechanical pulping processes, raising energy use over time.

identify whether alternative technological choices applied to a production system would lead to distinct and quantifiably different environmental outcomes. By conducting a scenarios exercise for the 1995-2010 period, we hoped to be able to distinguish the environmental effects of different trajectories of technological change, represented by alternative bundles of technological options. We posed the question: is it possible to identify a set of technical changes that would bring about a preferred set of environmental outcomes?

The major modelling effort did not yield conclusive results. While there are differences in the shapes of the environmental profiles for each of the scenarios, the main conclusion is that the three alternative technology scenarios generate environmental profiles that are *not* clearly distinct from the base case, or from each other. Within each technology scenario trade-offs are implicitly made between different dimensions of environmental performance. This picture holds for both the pulp and paper and the PVC case studies. Figure 3 illustrates the mix of outcomes across different parameters of environmental performance for the base case and three 'beyond base case' scenarios for the pulp and paper model.

A key result is that no single policy objective translated into specific technology-forcing measures (a focus on encouraging recycling, for instance) is likely to produce generic improvements in environmental performance. Gains achieved across some dimensions of performance may be reflected by losses in others. These trade-offs may to some extent be ameliorated using a mix of policy objectives - modifying losses in performance due to one set of technical changes with a compensating improvement by adopting others. The main conclusion to be drawn is that moving beyond base case performance (defined by best available technology (BAT) standards for 2010) is possible using available technologies, but that there is considerable uncertainty about defining a radically distinct trajectory as measured by environmental performance. Defining a sustainable 'end state' is not easy.

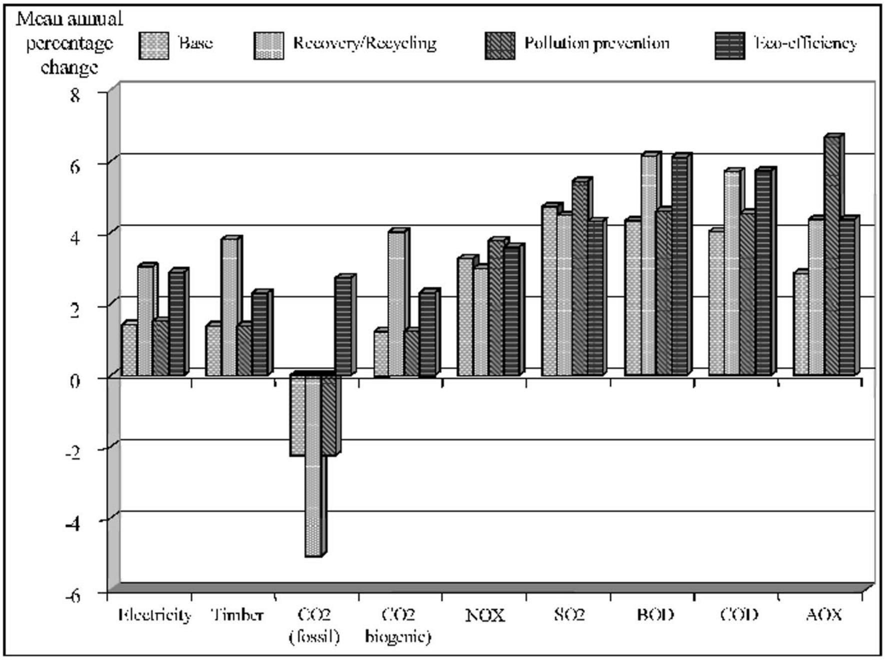

Fig. 3. Environmental Performance Changes for Technology Scenarios: Pulp and Paper, 1995-2010

5. Reconceptualising the Relationship Between Innovation Systems, Technological Regimes and Environmental Performance

We have discussed the validity of claims for two forms of technological transition induced by environmental pressures. The first we may define as a 'micro transition' between abatement technologies and 'clean' technologies. The second we may define as a 'macro transition' from one sectoral technological trajectory to another. We argue that there is little theoretical support and doubtful empirical evidence for the micro transition, and we show that the uncertainties that exist about the environmental outcomes of a macro-transition suggest a reconsideration of a purely objective-driven environmental innovation strategy. Nevertheless, we have also shown that technological change is strongly related to environmental performance at the sectoral or meso-level, pointing to a need for a conceptual model that will allow us to explain how technology and environmental dynamics are coupled. This model should also attempt to place these dynamics in a wider institutional context, linked to innovation and regulatory systems.

One way of conceiving of the link between technical change and environmental performance is in terms of *an innovation triangle* that links changes in abatement technology, process changes, product changes. This dynamic and interactive set of adjustments and adaptations within a technological regime is linked to and co-evolves with broadly autonomous changes in background infrastructures (see Figure 4). Rather than arguing for a progressive shift in the focus of innovation from one form to another (the notion of a *transition* from abatement to process change), this model shows that all technological regimes (and the clusters of firms and other actors that constitute from) face a range of market and social pressures for which a variety of technological responses will be appropriate.

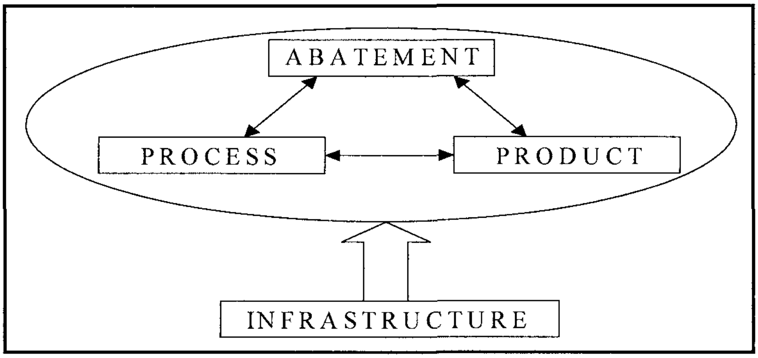

Fig. 4. The Innovation Triangle

Most industrial sectors face environmental pressures at all three corners of the innovation triangle, leading to a number of general conclusions:

- The source of pressures to innovate at each of corner differs: pressure on abatement has tended to come from regulators and neighbours; pressures on process change have tended to come from competitors and customers; whereas pressures on products have come from consumers and pressure groups;
- The innovative response at each corner differs: the technological resources necessary, the source of new technology, the rate of change and so on are all contingent on the technological problem which is being solved; in general abatement technologies are bought in from specialist suppliers, process technologies are developed through partnerships between capital goods suppliers and leading producers, and product changes are managed in-house as a critical source of competitive advantage;
- Changes in one corner of the triangle affect changes in both of the other corners: innovation is dynamically inter-linked and includes incremental and step-like adjustments and changes; this technological inter-relatedness modulates and tempers the opportunities for change that exist throughout the technological system.

We may also be able to generalise these conclusions to argue that the *pattern of pressures and opportunities across the three corners of the innovation triangle differs between sectors.* These differences are determined by economic, as well as social and political factors. In some sectors pressures and opportunities for abatement will be strongest, in others process and product changes will be relatively more important. But these distinctions will be a question of balance. All three types of change will be present, and each will have implications for environmental performance, as well as for competitiveness. Very crudely we may posit that in mature process sectors the focus of environmentally-significant innovation will be along the abatement-process change axis. In consumer goods sectors the focus will be along the product and process change axis, whereas in intermediate sectors within supply chains, the emphasis may be on the abatement-product axis.

6. Conclusion: Path Dependency and Transitions in Technological Regimes

The results of the SCOTCH study and the discussion in this paper lead to a number of observations that are germane to the current debate about system innovations and transitions for sustainability. First, here is little empirical evidence for what we have termed micro transitions between abatement and clean technologies in the paper and PVC sectors. There is a significant process of incremental technological change and some examples of modular reconfigurations at the sub-regime level (both frequently stimulated in response to environmental pressures – market and regulatory). This supports the lock in/path dependency school account of change in technological regimes.

Second, reflecting on the two examples of paper and PVC, the problem of systems innovation appears to be less one of a smooth reorientation of prevailing trajectories, and more a problem of reversal or extrication - with one regime being replaced by another which is morphologically and institutionally separate and distinct. In the choice between reorientation and substitution, the history of technology appears to favour substitution. This means that the problem of technological transitions should not begin with describing the inter-linkages between micro-, meso- and macro- innovations within the context of an incumbent technological regime (transition management). Truly revolutionary innovations are likely to start small, and they will come to define through co-evolutionary processes a new regime *for themselves*. In doing this, they will need to overcome 'barriers' (technological, institutional, economic, political) which stand in the way.

Third, there are a number of policy implications: the need to encourage new incipient regimes; the need to facilitate competition 'early on' (by reducing switching costs, by reducing barriers); and the need to intervene in processes of regime extrication and extinction (negative incentives to incumbent technologies – by imposing full environmental costs on them, for instance), so creating the conditions for their substitution.

Fourth, having argued this, we must also be constantly aware of the paradox of entrenchment – innovation and adoption of radical and risky new technological regimes is not possible without commitments (overcoming barriers and creating an economic and institutional context for adoption and a new process of 'locking in'). Adoption leads to channelling and the formation of new 'trajectories', but each time this occurs there is a new risk that what may with hindsight be seen as risky or costly technologies gain dominance. We have shown through our scenarios thought-experiment how difficult it is *a priori* to identify which set of technological alternatives is likely to yield the best results – just giving something a green label is clearly not enough. Scenario analysis identified that there are many examples of poor choices in history (supersonic air transport, nuclear power). Scenario analysis identified multiple uncertainties in defining alternative future trajectories even within the prevailing technological regime. This problem will be more serious with more novel and unknown technologies (Freeman 1982).

Fifth, not only is the definition of a preferred trajectory difficult, there is also the question of whether the path that a trajectory follows is 'governable' (and governable by whom – firms or government?), or whether to some extent it follows an autonomous or 'emergent' path. Those strategy authors (Mintzberg 1987) who have stressed uncertainty are also those who have emphasised the limits and dangers of following a 'rationalist' approach to strategy. This they view as strategy-making separated from implementation (leading to risk of a failure to learn), and strategy-making that encourages a new form of lock-in which may fail as circumstances change. They argue that it will not be possible to know the outcome of an experiment until the experiment has been completed and take a more 'adaptationist' view of strategy as something that unfolds as a result of the pursuit of 'routines' by business organisations employing heuristics. Strategy is not formulated, but formed with unforeseeable outcomes. This approach also suggests that the governability of thechnological regimes and trajectories remains open to question, and that there will be technological, economic and other developments that induce changes to any defined strategy. Rational behaviour under these conditions would be to maintain a diverse range of options (to mitigate multiple uncertainties). Here a delicate balance must be struck since it may be that the maintenance of options, and the preservation of the option of reversibility (or retreat) undermines the establishment of a new trajectory (investment, learning, standardisation, network externalities and so on). It also may entail quite substantial cost and manipulation of markets by government.