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Technological change and the role of public policy: An analytical framework for dynamic efficiency assessments

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It is increasingly being recognised that the development, adoption and diffusion of cleaner energy technologies are key determinants to success or failure in environmental and climate policy, at least in the long term. However, our understanding of the factors and mechanisms that promote or hinder environmentally benign technological innovation is still somewhat elusive. Moreover, it is still unclear what role there is for public policies and regulatory intervention in this field, and how to select an appropriate portfolio of policy action and instruments that does justice to all stages in the development cycle of technological change. The key objective of this report is to provide an analytical framework for analysing and assessing the way(s) in which public polices can promote innovation and guide technological development patterns in directions beneficial to the environment and society at large. For this purpose the report presents a template for comparative policy analysis based on fuzzy sets to serve as a focusing device for dynamic efficiency assessments. An empirical case is also provided for illustrative purposes, analysing the development of new renewable energy technologies the Norway. The case study substantiate claims that a broad range of policy measures are needed, and that institutional inertia and 'lock-ins' may hamper technological innovation processes.

Stikkord/Key Words
Technological change, innovation, public policy, climate change, dynamic efficiency

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Preface

This report has been written as a part of the project “Environmental innovation in the energy sector”, financed by the Norwegian Research Council within the SAMRAM programme, Grant No. 138922/730. The project focuses on the interplay between public policy and technological change. More specifically, the report proposes an analytical framework for dynamic efficiency assessments, pertaining to how and the extent to which combinations of policy instrument or ‘policy packages’ may provide ongoing incentives for technological change and innovation.

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Atle Christer Christiansen

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> “It is widely agreed that technical innovation is the ultimate key to successful (meaning affordable as well as quantitatively adequate) global measures to stabilise the concentration of GHGs in the atmosphere” (Toman, 1998: 610)

1 Introduction

Within academic as well as public discourse it is increasingly being recognised that the processes of technological change and innovation play key roles in addressing and solving environmental problems. This is most surely the case with the daunting task of mitigating global climate change, which comprises the perhaps most pressing and complex environmental issue on the international agenda. The climate change challenge concerns and affects the energy sector in particular, since energy-related CO_2-emissions accounted for about 80% of total emissions of greenhouse gases (GHGs) in Annex B countries in 1990 (IEA, 2000: 231). Thus, a key to success in climate change mitigation, at least in the long term, is to induce development, deployment and widespread dissemination of low-emission supply and conservation technologies, capable of competing head-to-head with conventional and more polluting options.

Since technology is likely to play a key role for the design and implementation of abatement strategies, it is crucial that policymakers have capacious knowledge of factors and mechanisms that promote, or hinder technological change, and the role of public policy in such processes. Choosing the right combination of policy instruments is in this respect a key task, for which this report aims to establish an appropriate analytical framework for public policy assessments. However, the objective is not to examine the legitimacy of different policy instruments or the degree to which such instruments contribute to the achievement of policy goals (e.g., cost effectively). Instead, the report aims to assess *how* and to what extent different combinations or ‘packages’ of policy instruments provide on-going incentives for technological innovation, i.e., achieves *dynamic efficiency* gains.

A contentious issue in discussions on climate change policy is the extent to which short-term mitigation strategies should aim beyond the confines of ‘no-regret’ measures. Owing to the inertia of energy systems and the possibility of irreversible damages caused by climate change, it may be critical that certain abatement activities start now in order to induce learning and reap the full benefits of technological innovation. Moreover, since the development of new technologies and learning about their use is required to reduce also the cost of *future* abatement action, picking only the low-hanging fruits may in the long term prove to be inferior in terms of economic costs and environmental impacts.

The report departs from a brief analysis of the complex processes and stages through which emerging technologies evolve, identifying key factors and mechanisms that promote technological innovation. We then examine a selection of different policy instruments that are available to policymakers, scrutinising in particular their (potential) impact on technological change and innovation. Combining insights from such investigations, the report then unfolds an analytical framework for dynamic efficiency assessments. The framework is presented in terms of a template that reflects the uniqueness and inter-relatedness of each stage in the technology development cycle, for which a blend of different policy instruments seems required to make justice to each stage, and reap the full benefits of technological innovation. The ambitions of the present report may thus be formulated in terms of answering the following research questions:

1. What is technological change?
2. What are the key factors and mechanisms that stimulate technological change?
3. Which instruments are available for policymakers to promote such change?
4. How could knowledge and insights on the processes of technological change and efficiency properties of policy instruments be combined for the development of an analytical framework for dynamic efficiency assessments?

In order to answer these research questions the report is organised as follows. Section 2 provides a general introduction to studies on and theories of technological change, presenting also a number of key analytical concepts commonly deployed in such studies. Section 3 then proceeds with a discussion of how public policy may provide framework conditions that promote technological change and innovation; i.e., achieve *dynamic efficiency gains*. Section 4 elaborates on the dynamic efficiency properties of specific policy instruments, emphasising the need to pay justice to all phases of technological change. Against this background section 5 offers a *template* for assessing the dynamic efficiency properties of public policies. Section 6 provides an empirical test case, in which we employ the template to analyse the interplay between public policies and new renewable energy developments in the Norwegian energy sector.

2 What is technological change?

The objective of this chapter is to provide a general background for policy and dynamic efficiency assessments, by means of unfolding some of the key characteristics of technological change (sections 2.1 and 2.2), addressing also key drivers (section 2.3) and barriers (section 2.4) for change.

Technology is today recognised as the perhaps most influential agent of change in the evolution of industrialised countries[1]. By now, most people in modernised societies have become habituated to the power of technology by the ways in which the political, economic, scientific and social spheres to an ever-larger extent have become technologically embodied. In terms of environmental impacts it is widely recognised that the introduction of new devices, machines, processes and practices have eliminated certain environmental problems, while also creating new ones. The conception of technology as a double-edged sword has again stimulated a growing interest in the study of technology as such, and the histories we tell regarding its development and sediments (see e.g., Orlikowski, 1992 and Feenberg, 1991; 1999). Since these ‘ambivalent potentialities’ open up for qualitatively different development trajectories, it is critical that decision- and policymakers fully understand the forces and mechanisms motivating and ‘steering’ the direction of technological change.

Any attempt at providing a rigorous or one-all ‘definition’ of technological change will most likely fail in grasping all the fundamental characteristics and complexities involved. Consider first the concept of *technology*, which, in its narrow sense is used to denote certain physical constructs or ‘artefacts’, such as tools, machines, utensils or utilities (e.g., Mitcham: 1994: 162-5). However, it is also increasingly connoted with industrial management and organisational projects. In an attempt to explore the wide variety of features associated with the ‘modern’ conception of technology, Mitcham (1994) has introduced a typology that includes four different types of technology: technology as *object*, as *knowledge*, as *activity*, and types of technology as *volition*. In this work we use technology mainly in its restricted form as either object or knowledge, for which we sometimes use the term *technical* to distinguish artefacts or hardware from their embodiment in the ‘social world’.

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[1] See e.g. Hughes (1983), Mitcham (1994) and Feenberg (1991, 1999).

Adding the suffix *change* in effect points to the essentially dynamic nature of technology. One might thus conceive of technological change in terms of the making and using of new products or processes, changes in techniques and productive organisations or ‘new combinations’ as in the Schumpeterian sense. Against this prelude, the next section embarks upon the first of three core questions by presenting and discussing some of the prevailing theoretical perspectives on factors and mechanisms that trigger off or induce technological change and innovation.

2.1 Opening the black box: Towards a typology of technological change

Established theories on technological change have traditionally subscribed to the confines of two dominating approaches[2]. On the one hand, there is the strand of analysis that conceives technological change as a predominantly *rational* and *goal-oriented* endeavour aiming to maximise profits, enhance productivity or improve efficiency. Herein the underlying objective is seen either as that of locating an ‘optimal’ technology or subset of technologies among a wider portfolio of options, or to develop technology that satisfy demands for productivity or efficiency.

On the other hand, there are theories that portray technological change as an adaptive process of ‘trial and error’, in which the cumulative addition of technical modifications, know-how, learning (by doing, using and interacting) and competence is used to improve upon existing technologies and production processes. Technological change may as such be delineated as a “slow and often almost invisible accretion of individually small improvements” (Rosenberg, 1982: 62). Past history, socio-political developments, and ‘*evolutionary*’ processes of selection, variation, and struggle are thus considered among the key determinants for the development of particular technologies. This emphasises that technological change finds its origin *inside* rather than outside the economy, and should thus not be treated as an exogenous feature or ‘manna from heaven’.

The concept of technological change may also be studied according to the position and explanatory power admitted to technology *per se*. This point towards another demarcation line

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[2] See for instance Elster (1983) for a discussion on these approaches from the point of view of different modes of scientific explanation.

in theories of technological change, represented by the genres known as technological determinism and social constructivism[3]. Put briefly, technological determinism upholds that technology itself has the power to affect and induce (societal) change according to some intrinsic property[4]. Social constructivists, on the other hand, emphasise the ‘social shaping’ of technology, in terms that social groups and actor-networks award to technologies their working and meaning. However, it has also been noted that these approaches represent only two ends of a spectrum, recognising that technology is both socially constructed and society shaping. In attempt to reconcile determinism and constructivism, Thomas Hughes (1983, 1987, 1994) uses the concept of ‘technological momentum’ as an alternative that also captures the time dependency of technological change.

Even though there is a substantial literature on technological change, analysts and researchers commonly agree that there is still a lack of analytical and empirical techniques to investigate thoroughly into the complex processes of technological change and its impacts (Grübler *et al*., 1999: 248). Still, researchers commonly distinguish between the creative process of bringing forth a new idea, device, product or process (invention), the practical applications of such inventions (innovation), and the processes of market dynamics pertaining to adoptions in (niche) markets and (widespread) diffusion. A simplified typology for technology analysis based upon these stylised stages and mechanisms as illustrated in Table 1.

Inventions commonly originate in research activities involving essentially two modes of endeavour: *exploratory* or *basic research* and *applied research, development* and *demonstration* (RD&D)[5]. Basic research is commonly associated with activities aimed at deriving fundamental knowledge and scientific discoveries, whereas the notion of applied

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[3] See Smith and Marx (1994) for a comprehensive discussion on various forms of determinism, and Bijker *et al*. (1987) for a detailed account of common themes and approaches in sociological and historical studies of technology (social constructivism). Drawing partly upon a critique of the sociological, political and philosophical implications of these (and similar) approaches, Feenberg (1991, 1997) goes a step further in presenting a ‘critical theory of technology’ that opens up for a democratising path of technological change. Herein he emphasises the *ambivalence* of technology that allows for different values, norms and standards to intervene in the technological design process “in the defense of the conditions of a meaningful life and a liable *xiv*).

[4] One of the seminal works in the tradition of (technological) determinism is Jacques Ellul’s *The Technological Society* (Ellul, 1964).

[5] Scholars devoted to studying the philosophy of technology have pointed out potential caveats and epistemological pitfalls in viewing basic and applied research as fundamentally distinguished features. For an overview on this issue see Mitcham (1994).

adheres more to engineering activities. Development is typically related to activities involved in bringing a product or process towards the stage of a prototype or demonstration project, before eventually being put into commercial use.

Table 1: Stylised stages of technological development and mechanisms

Stage	Mechanism
Invention	Seeking and stumbling upon new ideas; breakthroughs; basic research
Innovation	Applied research, development, demonstration and deployment projects (RD^3)
Niche market commercialisation	Identification of special niche applications; field project investments; learning by doing; user-supplier relationships
Diffusion	Standardisation and mass production; economies of scale; building of network effects

Source: Grübler *et al*. (1999)[6]

Innovation commonly denotes the first time a product is put into regular operations, oftentimes as a result of applied research, development and demonstration projects. Adoption in niche markets involves a phase in which many possible designs are tried out and tested. This phase typically involves competition between numerous technical solutions and companies. If and when a technology manages to gain foothold in the market, the initial diversity usually evaporates, and a period of increasing standardisation and falling costs lead to rapid market growth; i.e. widespread dissemination or *diffusion*.

This simplified typology suggests that in order to reap the full benefits from technological change and innovation, it is crucial that framework conditions are designed to secure incentives throughout the chain of developments from invention, via innovation towards marketable introduction and widespread dissemination. Moreover, since each step in the

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[6] Note that Grübler *et al*. (1999) also include stages and mechanisms pertaining to *saturation* and *senescence*. However, these stages are omitted here since we are mostly concerned with the task of stimulating the development, deployment and diffusion of *new* technologies rather than technologies moving towards the final stages in their life cycle.

development life cycle is unique, albeit inter-linked, it is unlikely that a single policy instrument can make justice to all stages. Rather, a portfolio of measures selected to match specific needs and circumstances seems required.

2.2 Delineating change: The nature and types of innovation

Within the literature on technological change and innovation, one commonly distinguishes between ‘incremental’ (or minor) and ‘radical’ (or major) innovations (e.g., Rosenberg, 1982; Freeman and Perez, 1988; Utterback, 1996; Grübler *et al*., 1999). The former is used to underpin the cumulative and adaptive character of technological change, emphasising learning effects connected with routine activities and modifications upon existing technologies and knowledge. The latter points to the intrusion of new ‘hardware’ or ‘software’ that fundamentally alters the way in which technologies are perceived (as objects for using or making). Even though the notions of incremental and radical imply differences regarding the magnitude or extent of change, incremental innovations may be just as important (or more) with respect to economic and technological progress as radical innovations. This owes predominantly to the cumulative nature of the former, which continuously adds to the existing knowledge base and as such improves the long-term performance of a certain technology. There is of course also interdependence between incremental or minor and radical or major innovations. Scrutinising both kinds thus allows one to consider technological change as a process that includes the creation and refinement of new products, as well as the changes taking place during the dissemination of such products.

Another distinction commonly made is that between *process* and *product innovations* (e.g. Rosenberg, 1982; Utterback, 1996). Irrespective of their prominence or rankings in historical or economic terms, it is important to comprehend that such innovations affect technological progress and economies in two fundamentally different manners[7]. Process innovations commonly signify changes in hardware or systemic re-integration that makes it possible to produce greater (similar) volumes of outputs (material of a certain quality) using similar (smaller) volumes of inputs (raw materials, energy). Product innovations on the other hand usually signify the introduction of a “qualitatively superior output from a given amount of resources” (Rosenberg, 1982: 3). A distinction may thus be drawn between advances that directly affect the *products* produced from an economy (petroleum, electricity) and the *processes* used to produce them (energy consumption, conversion efficiency). Perceptions and positions, however, often blur the distinction between these two categories. For instance, the introduction of a novel technology for electricity production utilising a new source of primary energy, may be considered a product innovation from the vendor’s viewpoint, whereas energy traders may consider it a process innovation if it enables similar (higher) amounts of electricity at lower (similar) prices.

Incremental or even radical changes in product design may indeed provide immediate improvements in environmental performance, but may not be sufficient to obtain significant environmental improvements in the long run. For instance, the monumental task of facilitating a transition from the currently fossil fuel-based energy economy to one based on low-or no-carbon fuels and technologies, necessitates fundamental changes in production systems and infrastructures. More specifically, it calls for investments in *system innovations* that go beyond the level of ‘end-of-pipe’ or ‘clean-up’ technologies[8]. The challenge for policy- and decisionmakers is to encourage long-term thinking as well as preventive actions and investments in order to obtain long-term environmental benefits. This also involves making careful assessments pertaining to the need and scope for incremental, radical as well as system innovations.

2.3 Drivers for change: Technology-push or demand-pull?

The debate on factors that influence technological change and innovation has traditionally focused on the question of whether available knowledge and technology or market opportunities comprise the crux of innovative activities. The former is commonly known as

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[7] The economist Nathan Rosenberg argues that product innovations should be treated as the most important, even though most economists traditionally have emphasised the importance of process innovations (Rosenberg, 1982: 3-4).

[8] Grübler (1998) has persuasively illustrated the long lead times required for new energy sources and technologies to penetrate, and eventually ‘corner’ the markets. For instance, it took some 90 years for oil to grow from a market share of 1 to 40 percent, still not reaching the 70 percent market share reached by coal in 1913.

the ‘*technology push*’ hypothesis, the latter the ‘*demand pull*’ hypothesis. Even though researchers largely have abandoned these ‘linear’ stimuli-response models on grounds that they do not portray the interactive nature of innovation processes[9], policymakers often equate innovation with ‘push-pull’ reasoning.

The ‘technology push’ model dates back at least to the early works of Schumpeter, in which he portrayed a life-cycle typology of technological change in terms of a three-staged developmental process including the phases of invention, innovation and diffusion. According to this “linear” model, inventions are usually conceived from acts of human ingenuity or new scientific knowledge (discoveries). The entrepreneur then turns an invention, which has no economic or social significance as such, into ‘new means of production’ or ‘new combinations’. An innovation signifies the point when a new technology or a new technique is put into regular production for the first time. Diffusion then denotes the process in which an innovation is disseminated into niche or commercial markets and as such achieves widespread application. Based on this model, a key role of public policies is to provide public funding for R&D activities in order to release and utilise ideas from the resource well of the inventor-entrepreneur.

Another variant of the linear model of technological (technical) change is the so-called ‘demand-pull’ model, which dates back to Schmookler’s cross-sectional comparison of industries using patent data[10]. Put in simple terms, such an approach assumes that innovations are in some sense triggered by societal ‘needs’ and opportunities for increasing sales from companies that succeeds in providing products responding to such a market demand. In order to provide dissemination of new products and alleviate (financial) risks, the ‘demand-pull’ hypothesis furthermore holds that publicly funded R&D should be allocated to areas identified by market research (Wallace, 1995).

In a much cited and powerful critique of ‘demand-pull’ theories, Mowery and Rosenberg (1979) pointed to the inconsistent use of ‘needs’ and ‘demands’ pertaining to technological change. Based upon a comprehensive review of empirical studies, the authors dismiss the

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[9] See e.g. Rosenberg (1982), Freeman (1982), Elster (1983), Lundvall (1988), Dosi *et al*. (1988), Nelson (1993), Edquist (1997) or Grübler (1998) for comprehensive discussions of the intricate mechanisms governing innovation processes.

[10] See e.g. Rosenberg (1982) or Freeman (1982) for a discussion of Schmookler’s analysis.

claim that market demand plays a dominant role in stimulating innovative activities. Considering the specific characteristics of push and pull theories and their interplay, the authors claim that instead of considering them as “each representing a sufficient condition for innovation to *occur*” (ibid.: 231, *italics* added) one should “consider them each as necessary, but not sufficient, for innovation to *result*; both must exist simultaneously” (ibid.: 231, *italics* added). Rather than attempting to induce change solely through a “big-push”, the authors stress that attention should be taken of a broader range of issues. Adequate knowledge and competence are thus crucial factors in the process of technological change and innovation are thus the need for, whilst careful attention should also be paid to the complex mechanisms prevailing within market economies, in particular with respect to the interplay between government and private development efforts.

Both ‘push’ and ‘pull’ models represent extreme positions in terms of identifying the causes or sources of technological change. Whereas ‘push’ theories views technological change as driven exclusively by *opportunities*, ‘pull’ theories view it as driven by *needs*. In a more general context, it also appears that ‘push’ has a greater impact on the early phases of the technology life cycle, while the influence of ‘demand-pull’ is seen more strongly in the later stages[11]. Both have as such been dismissed as singular explanatory theories in the literature on technological change and innovation, in favour of more well-suited models that incorporate complex feedback mechanisms involving science, technology, learning (by doing, by using, by interacting) and demands.

In an attempt to seize the essence of technological change, Grübler argues that it is “neither simple nor linear. Its four most important distinctive characteristics are instead that it is *uncertain*, *dynamic*, *systemic*, and *cumulative*” (1998: 21). Viewed against the profound and demanding climate change challenge there is perforce a need to transcend the narrow focus on (short-term) cost-effectiveness and put stronger emphasis on dynamic efficiency; i.e. the impact of factors and mechanisms on long-term technological innovation and *systemic* (structural) change.

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[11] Callon (1987) argues that the distinction may not be as clear-cut, particularly in the case of radical innovations. In such cases of influential and dramatic change he claims that “right from the start, technical, scientific, social, economic, or political considerations have been bound up into an organic whole” (ibid.: 84).

2.4 Barriers to change: Network externalities and lock-ins

It is today widely agreed that technologies are selected not only on the basis of technical or economic performance measures, but also by prevailing socio-political and cultural norms, rules and preferences[12]. Hence, not only is it increasingly being recognised that technological change and innovation occurs *inside* rather than *outside* the economy, but non-economic values also intersect and penetrate the economy by means of being technologically embodied. However, such insights are not only important for the understanding of technological change *as such*. Owing to the embodiment of technologies in a larger socio-economic context and the responsiveness of technological change to politics and culture, there are also various kinds of barriers and inertia that may constrain the evolution of new technologies as they progress from the 'drawing table' towards the market place. Such barriers and sources of inertia may effectively prevent the actualisation of the full potential of new technologies, if not properly addressed by policy- and decisionmakers.

Scholars studying technological change in the course of history have observed the formation and evolution of so called 'technological systems', constituting a set of components or building blocks in which every component is dependent on 'all others'[13]. This phenomenon is also known as *technological inter-relatedness* "under which sub-technologies become a supporting infra-structure" (Read, 2000: 51). Among the components making up an energy system, for example, are both physical artefacts, such as hydroelectric turbines, transmission and distribution lines, as well as organisations or institutions. Due to the interdependency and interaction among technologies, infrastructures and institutions, choices pertaining to systems management are often made in order to support the operating principles of the system as such. The latter is often designated *network effects* or *network externalities* in that they raise barriers by requiring new technologies to adapt to the existing system.

Another characteristic of modern, complex technologies is that "the more they are adopted, the more experience is gained with them, and the more they are improved" (Arthur, 1989: 1). The mechanisms through which these increasing returns arise are often denoted learning by doing and learning by using. The existence of such systemic interdependencies may allow

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[12] See e.g., Bijker *et al*. (1987), Freeman (1991,1999) and Aldrich (1999)

certain technologies to “corner the market” of potential adopters, which imposes constraints on the fundamental process of variation and selection among candidate technologies, locking-in patterns of energy use and production to particular configurations, and in some cases inferior technologies[14]. The constrained evolution of new technologies is also referred to in the literature as *path dependency*, which comes from “the increasing return mechanisms that reinforce the direction one on a given path” (North, 1990:112). In other words, once the development of a system is set on a particular course, the network externalities and persistence of norms, rules and preferences tend to make it difficult to change course. In fact, it has been argued that “industrialised economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale” (Unruh, 2000: 817). This condition is by the author

The idea of systemic features such as network externalities or lock-in mechanisms suggests the need for concentrated and collective action to facilitate the expansion of new technologies. To the extent that prevailing market or legal structures inhibit technology adoption and diffusion, carefully designed public policies and enlightened government intervention may break the ‘deadlock’ by guiding technological developments in a direction beneficial to society and the environment.

In conclusion, this section has emphasised the need for policymakers to understand the individual stages of technological change, and the nature of different kinds of innovations. Applied to the case of climate change mitigation, it seems evident that incremental innovations and cumulative improvements in existing infrastructure cannot alone surpass the technological and institutional constraints of the current ‘carbon-logic’. Moreover, it is crucial to design and implement policies that combines technology-push and market-pull and are capable of overcoming barriers that may constrain the evolutionary processes of technological change. In order to posit technological innovation firmly within the realm of politics, the next section explores ways in which long-term environmental and economic goals can be met in

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[13] See e.g., Hughes (1983,1987,1994), Grübler (1998) and Grübler *et al.* (1999).

[14] For a comprehensive discussion of ’lock-ins’ and increasing return mechanisms, see Arthur (1989,1990,1996).

terms of motivating technological change and innovation; i.e. actualise dynamic efficiency gains.

3 Beyond ‘push’ and ‘pull’: Providing the leverage for dynamic efficiency gains

The previous chapter presented a stylised typology of technological change as comprising of a set of distinct and inter-related stages, each encompassing a complementary set of (triggering) mechanisms. Taking this as a point of departure for discussions of policy implications, it seems likely that a blend of policy instruments is preferred in order to make justice to each stage. Moreover, it is essential that policymakers comprehend the interplay between public policies and factors that facilitate the development, deployment and dissemination of new, environmentally benign technologies. Before plunging into concrete discussions of policy options and effects on technological innovation, we first illuminate key distinctions between the notions of effectiveness and efficiency - in the *static* and *dynamic* sense. The purpose of this interlude is to argue that policy actions that are perceived as cost-effective (i.e., cost minimising) in a short-term perspective might not be consistent with actions required to minimise the social costs of achieving more long-term objectives.

3.1 A brief on the concepts of effectiveness and efficiency

A useful way in which a distinction between effectiveness and efficiency can be made is to relate the two notions to the concepts of objectives or goals and results. *Objectives* (or goals) may conveniently be defined as the set of states of things that the operation of the system is intended to produce, whereas *results* may be taken as the set of states of things that the operation of the system actually produces (e.g., Quantanilla, 1998: 126-129). The *effectiveness* of a certain policy measure may thus be defined as the degree to which the objective is contained in the actually obtained results. *Efficiency*, on the other hand, is commonly used to denote a certain input-output ratio, such as in thermodynamics, where the efficiency of an engine is typically measured as the ratio between energy input that is transferred to useful work and the amount of energy actually consumed. Economic efficiency typically denotes the allocation of goods or services to their uses of highest relative value.

Even though the efficiency of a policy scheme or instrument will increase as effectiveness increases, one may have situations in which high effectiveness is consistent with a low degree of efficiency. The key to this observation is that efficiency depends on some kind of economic assessment, depending not only on the resources (e.g., energy input, work-hours) required to achieve the objective, but also on subjective judgements of the economic outcome or other benefits. Hence, the concept of economic efficiency is somewhat more elusive than it might appear at first glance, and in particular as concerns the uncertainties involved in predicting future patterns of technology developments. First, criteria for measuring efficiency are only rarely available *ex-ante*, since such assessments require both the type and quality of output to be fixed. Economic efficiency is thus “necessarily secondary to clear definitions of both the problems to which technology is addressed and the solution it provides” (Feenberg, 1999: 79). Second, the merits of technologies are frequently determined by socio-technical and politico-institutional reasoning, in terms that “economics cannot explain but rather follows the trajectory of development” (ibid.)[15]. Thus, since no one seems fit to provide accurate estimates of neither the rate nor direction of future technology development trajectories, conclusions pertaining to actual efficiency (gains) can only be drawn *ex-post* and must as such be verified by empirical investigations[16].

3.2 Static versus dynamic efficiency

Economists have traditionally focused mostly on the static efficiency impacts of environmental policy and instruments, determined by the costs and benefits from marginal and instantaneous abatement actions, for which the state of technology is given (e.g., Parry, 1998: 1). In the static sense, *cost-effectiveness* is achieved when the marginal costs equal the marginal benefits owing to certain activities. In pollution control and cleaner production the challenge facing policy makers is typically to identify an ‘optimal’ mix of policies and measures so that emission reduction targets are met at the lowest possible societal cost. However, one should keep in mind that cost-effectiveness is indeed a relative concept, in the sense that it is valid only in relation to a given target. Hence, owing to the uncertainties

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[15] Feenberg (1999) posits this argument in terms of ‘bounded rationality’, for which he stresses that the merits and relative success of technologies invariably are context-dependent.

[16] Furthermore adumbrating the task of making ex ante decisions on cost-effectiveness and optimality is the issue of timing with respect to adopting new technologies. In order to harvest benefits from learning (by doing, using and interacting) and thus avoid the limitations of current knowledge and technologies, an appropriate strategy for the future may thus involve a ‘start walking and see’ approach (Grubb, 1997). The core argument is thus that even though the future costs of new (and existing) technologies are uncertain, they depend largely on actions taken now.

involved in predicting how the future will unfold and the inertia pertaining to technological and institutional structures, there is no guarantee that a policy strategy designed to achieve a cost-effective outcome within a limited time-span will minimise the societal costs in a more long-term perspective.

In a climate change perspective, the target may seem well defined, in terms that the Kyoto Protocol establishes an upper limit on national emissions for a given commitment period; i.e. 2008-2012. However, it is no easy task to decide upon (ex-ante) *how* future emission reductions are to be achieved and by which means (e.g., technological solutions), or to predict *when* abatement action should start[17]. Moreover, given the long-term nature of climate change, the profound challenge is to develop, implement and disseminate technologies that also reduces the cost of *future* emissions abatement, and as such allows the global community to define more ambitious targets post-Kyoto. Hence, a cost-effective strategy for compliance with the Kyoto targets may not be commensurable with a strategy designed to minimise the (societal) costs of reaching the long-term target of “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (UNFCCC, 1992: 9) [18].

There is a growing body of literature that addresses ways in which coherent public policies may provide on-going incentives for the development, adoption and dissemination of new, environmentally benign technologies[19]. This strand of theoretical and empirical research critically examines and assesses the impact of policy actions and instruments on the processes of technological change from invention to diffusion[20]. In terms of environmental policy and pollution control, the concept of dynamic efficiency may thus be used to designate whether,

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[17] See e.g. Toman (1998), Toman *et al*. (1999) and Weyant (2000) for comprehensive discussions on the economics of climate change.

[18] The full text of the Convention is available at http://www.unfccc.de/resource/conv/conv.html, [29.11.00]. See also Weyant (1999) for a multi-model evaluation of the costs of complying with the Kyoto Protocol, and Ha-Duong *et al*. (1999) for a detailed account of dynamic consistency problems behind the Protocol.

[19] See e.g. Downing and White (1986), Malueg (1989), Milliman and Prince (1989, 1992), Ashford (1993), Jaffe and Stavins (1995), Wallace (1995), Fischer *et al*., (1998); Norberg-Bohm (2000), Kemp (2000) and Jaffe *et al*. (2000).

[20] Note here the distinction between regulatory approaches aiming to change behaviour amidst producers and consumers towards producing and using less of emission intensive goods and services – *sufficiency strategies* - and *efficiency strategies* aiming to minimise abatement costs by investing in technological change and innovation. Effective and efficient policymaking and implementation should thus ensure that both strategies are pursued simultaneously.

and the extent to which policy actions and instruments provide on-going incentives for improved environmental performance through technological development and structural change[21]. Such change may materialise either in terms of new technologies (products or processes) with lower costs or superior quality, means to facilitate the switching from more to less polluting fuels, increasing rates of market adoption, or widespread dissemination (diffusion) of new technologies.

One may also note that the notions of cost–effectiveness in the private and public domains are not necessarily comparable. Private firms and companies are commonly governed by a required rate of return on capital, for which they tend to invest in technologies that ensure short-term efficiency (profit), i.e. pay-back on investments within the a predefined planning horizon. A socially or environmentally optimal strategy, however, may involve other investments and choices that aim for ‘long-term’ or dynamic efficiency[22].

3.2.1 Short term versus long-term strategies

To exemplify the main difference between static and dynamic efficiency in a climate change context, one may examine two types of abatement strategies commonly discussed in the literature. A ‘no-regret’ policy typically responds to global climate change by limiting national actions to measures that are cost-effective even when the benefits from reduced GHG emissions are not accounted for[23]. Typical ‘no-regret’ measures are accelerated adoption of energy-efficiency measures and demand-side management, such as switching from incandescent to high-efficiency fluorescent lightbulbs. This strategy may indeed prove to be (the most) cost-effective in a short-term perspective, in the sense that such measures yield the lowest abatement cost or the highest rate of returns. However, emphasising only short-term gains and entrenching existing technologies may compromise strategies aimed at developing new environmentally benign technologies to reduce costs of *future* abatement actions. In the

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[21] A similar (conceptual) definition is given in the White Paper on “Norway’s follow up to the Kyoto Protocol”, see St.meld. nr. 29, 1997-98: 34.

[22] Elster (1983) emphasises that strategies and dispositions aiming at maximising profits frequently are at odds with the desire to ensure effective long-term exploitation of (capital and labour) resources. Concerns for short-term gains (profits) may thus impose suboptimal solutions (‘local optima) rather than a global optimum.

[23] The expected (net) benefits from implementing no-regrets are assumed to follow from market failures and inefficient pricing that may be corrected.

long run, short term strategies that are restricted to no-regret measures may thus be inferior both in terms of costs and environmental impacts[24].

The objective of cost-effective implementation of the climate regime, in the static sense, may thus slow down or constrain technological developments that in time may cut the cost of curbing future emissions and enhance the social profitability. Certain actions may thus need to start now, requiring the adoption of measures that go beyond the group of ‘no regrets’. However, this does not imply that ‘aggressive’ short-term emission reductions need to be pursued. Rather, policymakers should ensure a framework that precipitates investments in research, development and demonstration (‘technology push’), and design instruments and incentives to ensure the deployment of new technologies at the market place (‘demand pull’). Innovation oriented strategies should also consider ways of facilitating learning, capacity and network building, development of nursing and bridging markets, overcoming institutional or market barriers; all of which may prove crucial to the evolution of new and environmentally benign technologies (e.g., Grübler et al., 1999; Jacobsson and Johnson, 2000).

3.2.2 Timing of abatement actions: Act now or later?

Timing is another crucial issue that needs to be addressed in terms of designing and choosing an effective or even ‘optimal’ strategy for abatement actions. Put simply, the core question is how much emission reduction society should incur today, and how much should be postponed until new and less costly (more efficient) technology is available?

Wigley *et al*. (1996) argued that it matters little in terms of long-term climate change whether emission reductions takes place now or later, provided that *cumulative* emissions remain within certain limits. Based upon this premise the authors claim that a strategy in which abatement is deferred would be economically preferable. The argument is that substantial near-term emission abatement may increase the costs of climate policies, in terms that the costs of premature retirement of capital stock has to be covered in addition to the costs of abatement actions. Another argument raised in favour of deferral is that technological progress over time will provide a wider portfolio of options that eventually will reduce the

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[24] See Ha-Duong *et al*. (1999) for a detailed discussion on the issue of finding an ‘optimal’ abatement strategy in terms of six theoretical dimensions; discounting, inertia, technical change, irreversibility effect, dependent learning and risk aversion.

costs of abatement actions. The inertia displayed by most technological systems, and the long lead-times required to develop low-carbon technologies into commercial maturity, are thus posed as arguments in favour of deferring abatement action. The premises and conclusions put forth by Wigley *et al*. have however been contested on several grounds.

Ha-Duong *et al*. (1999) emphasise the Janus role of inertia, in terms that even though inertia may inhibit early action, it may also act as a "cost multiplier if, in the case of bad news about climate change, the abatement has to be accelerated" (ibid.: 434). Thus, because technical change requires long-standing and strategic efforts, the overall costs of acting too late may be prove to be excessive and even undermine the achievement of the long-term objective of the UNFCCC. Hourcade and Chapuis (1995) have proposed similar arguments with an appeal to the precautionary principle. Hence, "because of the inertia of the residence times of greenhouse gases in the atmosphere and of ecological mechanisms, and the slow response of technological and economic measures, decisions taken only after gathering clear-cut proofs of the risks have a non-zero probability of coming too late" (ibid.: 434). The authors advocate a sequential approach for decision making in climate strategies, involving a trade off between the three 'kinetics' of global climate change: accumulation of GHGs, development of scientific knowledge, and technological progress. The crux of such a strategy should be to maximise 'learning time', which requires moving beyond 'no regrets' even in short-term decisions to include also investment in climate research and innovation policies.

Grubb (1997) also explores the fundamental economic issues involved in finding the 'optimal' timing of CO_2 emissions abatements, for which he illustrates potential impacts of short-term versus long-term strategies and the trade-off between deferring actions or taking actions 'now'. Grubb emphasises that the conclusion by Wrigley *et al*. was "justified in part by reference to economic modelling studies that used resource allocation/equilibrium models" (ibid. 161). The use of such models are recognised to embody several caveats pertaining to the way in which real-world mechanisms are accounted for, such as induced technological change, learning and increasing returns to scale[25]. Addressing in particular the importance of *induced technology developments* through endogenous mechanisms - stimulation of R&D and technological learning – Grubb recommends a balanced assessment that would defer certain

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[25] For discussions on these topics see also Arthur (1989, 1996), Grübler *et al.* (1999), and Peters *et al.*, (1999).

actions whilst supporting technology development to avoid excessive abatement costs in the future. This conclusion draws from the ‘common sense’ insight that we cannot gain knowledge from ‘learning by doing’, ‘learning by using’, and ‘learning by interacting’ unless we engage ourselves in abatement activities.

Grübler (1998) also argue strongly against the economic assertions contained in Wigley *et al.*, claiming that they treat technology mainly as a quantity exogenous to the economy and society, and thus ‘overlook’ or undermine the importance of learning and induced technological change[26]. As climate change is indeed a long-term and global issue that requires emission reductions as well as reductions in mitigation costs, the author argues “that we should act sooner rather than later if we expect to reap the awards of technological progress later on” (Grübler, 1998: 360). Moreover, it is thus crucial to distinguish between the timing of action and abatement, respectively. Hence, even though certain actions need to start now, “action does not necessarily mean aggressive short-term emission reductions, but rather enhanced R&D and technology demonstration efforts that stimulate technological learning” (Grübler and Messner, 1998: 495).

In conclusion, this chapter argues that strategies perceived as cost-effective in the short term may not be consistent with actions aiming to minimise the social costs of achieving more long-term objectives. Taking into account that the development and diffusion of low-impact technologies is a key to success or failure in environmental and climate policy, at least in the long run, the concept of *dynamic efficiency* is introduced to assert the extent to which policy action promote technological change and innovation.

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[26] In his book Grübler (1998) presents in terms of historical analysis a number of illustrating examples that reveal the impact of technology on global change and human activity.

4 Technological innovation and public policy

The foregoing chapters have argued that the processes of technological change and innovation can be portrayed as a series of distinct and interrelated stages. Moreover, the analysis reveal that there is clearly a role to play for policy action in order to stimulate the evolution of new technologies with improved environmental performance, and that public policies should be designed to make justice to each stage in the evolution of new technologies. The question is then; what are the instruments available to policymakers in designing innovation-friendly environmental policies? A policy instrument is here though of in the general sense as "everything a policy actor may use to obtain certain goals" (van der Doelen, 1998: 131). Even though there is a plethora of different policy instruments and measures, and numerous attempts have been made to provide appropriate classification schemes, Vedung (1998: 30) suggests the following threefold typology[27]:

- Regulation ('Sticks')
- Economic means ('Carrots')
- Information ('Sermons')

The defining property of regulation is that "the relationship is authoritative, meaning that the controlled persons or groups are obligated to act in the way stated by the controllers" (ibid.: 31). Economic policy instruments, on the other hand, "involve either the handing out or the taking away of material resources, be they in cash or kind" (ibid.: 32). Finally, information comprises of government use of persuasion and reasoned arguments to motivate certain patterns of behaviour or behavioural change. The three categories are divided according to the "degree of constraint intended by the policymakers", for which regulation are treated as more constraining then economic means, and economic means more constraining than information (ibid.: 37).

As regards government support for development and deployment of low-carbon technologies, it may come about *directly*, as publicly funded R&D programmes, or *indirectly* through a

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[27] Note here that schemes involving negotiations between public authorities and private entities, such as covenants, are treated under the category of information as they are regarded as "cases of governing through persuasion" (Vedung, 1998: 37). For specific discussions on voluntary agreements and innovation the interested reader may confer Wallace (1995), Sunnevåg (1999) and Kemp (2000).

instruments that create incentives for specific patterns of technological developments and/or reduce the risks of investing in technological innovation. In order to select an effective blend or portfolio of instruments, policymakers are required to assess the effectiveness or efficiency with which particular instruments contribute to the achievement of the initial policy target or objective; e.g., behavioural/technological change (outcome) or improved environmental performance (impact). In the case of environmental policy in general, and climate policy in particular, the relevant effects are typically related to mitigating adverse environmental impacts (climate change) through emission reductions and pollution control. Below we briefly examine 'command and control' approaches and economic instruments. Note that the analysis considers only the extent to which different instruments may improve environmental performance through technological change and innovation, i.e. achieving *dynamic efficiency*, thus omitting other indicators such as the degree of goal achievement, legitimacy, response times required to comply with standards, enforceability, or predictability.

4.1 Regulation – 'command and control' approaches

Non-economists and government authorities often pose the use of regulation as effective instruments in environmental policy and pollution control. Such 'command and control' approaches are commonly classified as either *technology-based* or *performance-based*, both of which can be designed to be 'technology-forcing' in terms of mandating specific behavioural changes or technological options. The former class typically requires the use of particular products, processes or procedures, for which standards such as 'best available technology' (BAT) have been used extensively in the US and certain European countries (e.g., Wallace, 1995; Porter and Van der Linde, 1995). Performance standards, on the other hand, specify a certain quantitative pollution limit to be achieved by all regulated units, but does not stipulate the means or technology to be used for compliance, such as in the U.S. air toxin standards (e.g., Wagner, 2000)[28].

To the extent that supposedly cost-effective technologies are not able to penetrate the markets due to some unsurpassable barrier or 'market failure', direct regulation may be effective in

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[28] Note that due to the linear relationship between the carbon content in fossil fuels and CO_2 emissions, regulatory requirements on performance (specific emissions) may also be translated into (energy) efficiency (technology) standards.

order to overcome such barriers and shift patterns of production or consumption towards the adoption of such technologies. It is argued that stringent environmental regulation in this sense can induce or ‘force’ private investments in R&D that leads to development of new technologies. California’s strategy of imposing mandatory future market shares for ‘zero-emission vehicles’ (10% in 2003) is a much-cited reference in this regard (e.g., Kemp, 2000). One may in this respect argue that strict standards provides a benchmark towards which R&D efforts can be directed and as such stimulate technological development.

Besides using standards as a requirement on companies to apply specific technologies or achieve a reduction target at a given point in time, standards may also be changed over time as technological development, adoption and diffusion proceeds. The chief role of governmental intervention is thus to assign appropriate standards and ensure that firms comply with performance standards and/or that the mandated technologies are factually put in use. Formulating rules, procedures and modalities for compliance is thus a core issue.

There are, however, several lines of criticism and conflict pertaining to the impact of direct regulation on technological change and innovation.

First, since it may be difficult for policy- and decisionmakers to obtain precise information on cost functions pertaining to different firms and/or industrial sectors, the overall costs of using standards may be excessive in terms that cost-effectiveness is not achieved (e.g. Hoel, 1998). It may also prove difficult to reach agreement on the appropriate standards for different applications and sources (new and existing plants), while monitoring and enforcement costs may be high (IPCC, 1996). Moreover, the required upgrading of standards is likely to be hampered by the often slow and discontinuous nature of regulatory decision processes.

Second, if there are no incentives for firms to develop technologies that move beyond the current standards, mandatory requirements may deter investments in innovation, and thus yield poor dynamic efficiency (e.g., Heaton and Banks, 1999; Kemp, 2000). Hence, they may become ‘technology freezing’ rather than ‘technology forcing’. However, the latter depends on the regulated agents’ perception of the need to stay ahead of the policy process in order to maintain competitive advantages, and whether the innovating company is the same as the user of the technology (Wagner, 2000: 108). Using additional instruments, or so-called secondary regulatory strategies such as R&D support and public procurement could, however, ease this problem (ibid.: 113).

Third, stringent regulation may exacerbate risk pertaining to R&D investments, in terms of raising fears that a new technology (product, process) will not be able to meet current or future environmental standards, or that standards will be tightened in response to technological change. Standards may also instigate technological 'lock-in' or path dependence, in terms that technologies that meet current standards may gain an early lead in adoption that eventually 'corner the market' so that other technologies become locked out. Lock-in to a limited number of technologies may prove unfavourable in the longer term, especially if it occurs during the early phases of developments in which the full potential of 'immature' technologies are yet to be realised.

Fourth, while standards may be an effective policy option in reducing emissions that cause local damage and/or originates from clearly defined point sources, the task of identifying appropriate standards or pollution limits becomes much more complex when it comes to diffuse emissions from a vast number of sources. This is clearly the case for emissions of greenhouse gases, as compared to controlling toxic emissions and chemicals emitted from smokestacks or industrial effluents.

Finally, the use of command-and-control policies and environmental standards (technology, performance) may prove infeasible as the U.S. and most European countries move towards restructuring and liberalising the energy sectors. In light of such developments, regulation is likely to be revised and become more technology neutral, for which current trends towards market-based approaches may be boosted (IEA, 1999). One may thus also avoid unwanted effects of rent-seeking behaviour[29].

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[29] Rent seeking is commonly used in reference to a kind of practice in which firms find it easier to lobby for wealth transfers than to compete for wealth in an open marketplace. In the environmental domain, rent seeking typically involves pursuing government intervention that will provide a comparative advantage to a particular industry. The "rents" are economic returns in excess of what the marketplace would otherwise allow.

4.2 Economic and market-based instruments

To the extent that ‘command and control’ approaches limits incentives for technological change and innovation, economists have traditionally supported the use of market-based instruments in environmental policy, such as environmental charges/taxes, subsidies, tradable permits, and deposit-refund systems (OECD, 1997; 1999). Such market incentives aim primarily to *induce* – rather than *mandate* or *command* – behavioural (and technological) changes by providing financial or similar motivations for regulated sources to improve environmental performance. The objective is as such to ensure cost-effective compliance with policy goals, and to reward companies that manage to improve environmental performance beyond levels required by command-and-control approaches. Cost-effectiveness is achieved in terms that emitters in a perfectly competitive market would reduce emissions to a level at which the tax rate or permit price equals the marginal cost of abatement. Provided that all emitters are subjected to the same tax level or permit price, they will also have identical incentives to pursue abatement efforts.

However, the ‘superiority’ of incentive or market based measures is justified not only in terms of cost-effectiveness, but also for their capacity to stimulate technological change and innovation. It is thus assumed that instruments such as taxes or tradable permits provide continuous incentives for allocating efforts and financial investments in innovative activities, with the aim to develop and deploy abatement technologies in order to avoid taxes or permit costs. The case for economic incentives is also claimed to be strong in terms of flexibility provisions; i.e., that they leave the freedom of choosing the means and moment of compliance to the regulated agent, also providing incentives to move beyond environmental standards[30]. Still, empirical evidence concerning the dynamic efficiency properties of market-based approaches is in general limited (e.g., Jaffe and Stavins, 1995; OECD, 1999; Fukasaku, 2000; Christiansen, 2000b; Stavins, 2000).

It has also been argued that “economic incentives may be better suited to stimulating technological diffusion than innovation” (Kemp, 2000: 44). Moreover, and in particular for taxes, it is of course required that polluters respond to or are capable of responding to price

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[30] See Burtraw (2000) for empirical evidence of such flexibility gains within the US SO_2 emission allowance trading programme.

signals, and that the price incentives should be sufficiently high so as to stimulate investments in environmentally benign technologies or behavioural change. Resorting to cap-and-trade schemes using tradable permits may to some extent alleviate the uncertainty regarding agent responses. However, extensive discussions on the potential benefits of taxes versus permits - for which there is an extensive literature[31] - are omitted here.

Another type of economic instrument, subsidies, also deserves mentioning. The basic idea of a subsidy, as with taxes, is to alter the price structure in favour of certain products or technologies that may lead to higher environmental standards. In terms of mitigating CO_2 emissions it has been argued that subsidies will fail to yield either static or dynamic efficiency, since it requires that “the technological potential for CO_2 emissions must be exploited excessively and with additional increasing costs if the CO_2 target is to be met” (Heister, 1992, pp.231-232). It is argued that “subsidies can be considered a negative tax [or] as a soft form of direct regulation, and hence inherit the unfavourable properties of the latter” (ibid.: p. 231). This may indeed be the case for certain kinds of subsidies, such as direct price support for fossil fuels, or in cases where efficiency is measured only in terms of private costs and benefits. However, one may also argue that subsidies are likely to stimulate innovation in the sense of being perceived as a ‘golden carrot’ rather than ‘stick’, which is the case with taxes or fees. Jaffe and Stavins (1995) argue that in some cases the effects of adoption subsidies on technology diffusion “appear to be substantially greater than expected impacts of equivalent Pigouvian taxes” (ibid.: S61)[32].

Moreover, if one regards publicly funded R&D programmes as subsidies, there is a comprehensive literature revealing ways in which R&D support provides a key source of innovative ideas for industry[33]. For instance, publicly funded R&D commonly represents an important factor in the process of selecting innovations that may lead to niche market application, commercialisation and pervasive market diffusion. It is also a mechanism that is fundamentally oriented towards opening windows of opportunity and generating ‘freely

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[31] See e.g. Downing and White (1986), Malueg (1989), Milliman and Prince (1989, 1992); Heister (1992); Jaffe and Stavins (1995), EEA (1996), OECD (1997; 1999); Hoel (1998), Goulder and Mathai (2000), Parry (2000), Burtraw (2000); and Jaffe *et al*. (2000).

[32] The authors add, however, that even though “the finding is at odds with economic thinking, it does appear to be consistent with the conventional wisdom among noneconomists” (Jaffe and Stavins, 1995: S61).

[33] See Salter and Martin (1999) for a critical review of this literature.

available' pools of knowledge. The rationale for such public investments rests on a reasoning that incorporates two fundamental aspects of technology dynamics. The first is the crucial role R&D play in facilitating practical experience and learning, which may improve the economic performance and thus make immature technologies more competitive. The second aspect points to the vast uncertainties embedded in strategic decisionmaking that involves future developments. Such uncertainty involves expectations of future demands for technology services, costs and learning rates, which eventually "lead firms and societies to hedge risks by investing in portfolios of new technologies with potentially useful attributes" (Grübler *et al.*, 1999: 267). This is particularly relevant in cases when a market for new technologies does not exist, or when it is pertinent to increase the number of technological options available. Hence, taking into account the growing international markets for environmental technologies and the gradual but unavoidable depletion of fossil fuels, a policy that incorporates public funding for cleaner and new renewable energy (NRE) technologies may indeed provide the leverage for dynamic efficiency, at least in the long-term. However, one should also be aware of and hedge against the danger that R&D programmes may support mostly second-best technologies or provide windfall gains to the recipients.

4.3 New renewable energy policies

Urged by the risk of human induced climate change and the need for greening of the energy sector, several countries have over the last decades launched specific public programmes and policy packages to enhance development, adoption and diffusion of new renewable energy (NRE) sources and technologies. Besides publicly funded research, development and demonstration (RD&D) programmes, which are commonly considered a cornerstone in long-term strategies, experiences from a number of countries also indicate that some forms of economic incentives are required to create a market for NRE sources and technologies. Some countries, such as Denmark and Germany, offer state subsidies in terms of guaranteed minimum prices (feed in tariffs) to renewable generators. Other support mechanisms lean more towards legislative action and measures. This is the case with purchase requirements or obligations, such as the UK renewables NFFO, renewable portfolio standards (RPS) or green certificate trading. However, such 'hybrid' instruments combine elements of 'command and control' with marked-based approaches and flexibility provisions; e.g., by allowing for trading of credits.

4.3.1 The renewables NFFO

Following the privatisation of the electricity supply industry in the UK, a programme to stimulate electricity generation based on renewable energy sources was established for the first time in 1989[34]. Originally intended as a means to support nuclear power, the so-called Non-Fossil Fuel Obligation (NFFO) required the twelve Regional Electricity Companies (RECs) in England and Wales to purchase a certain amount of nuclear and renewable electricity. Given legislative status under the 1989 Electricity Act, the NFFO provides for renewable electricity to be purchased at a guaranteed *premium price* for a contract period of eight years[35]. By entering such contracts, the RECs become eligible to be compensated for the premium price paid to the renewable generators. The difference between the premium price and the prevailing (monthly average) pool purchasing is thus reimbursed to the RECs through a levy on electricity sails. This Fossil Fuel Levy (FFL) is paid by all customers via the electricity bill, which is currently set at 0.7% (Department of Trade and Industry, 1999)[36].

To date, five NFFO Orders have been made. Apart from NFFO1, in which each project was assessed individually without direct competition, contracts under the NFFO Order have been awarded on the basis of competitive tenders, submitted by the generators at the invitation of the RECs. Tenders are structured by type of project and contracts are awarded as a result of competitive bidding in technology bands. Wind projects thus compete against other wind projects, hydro against hydro. Criteria for establishing the premium price have differed among the Orders. Generators with contracts awarded under NFFO1 and NFFO3 for instance received their bid price, whereas all NFFO2 contracts were paid the same marginal or strike

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[34] The renewable NFFO was justified on essentially two main grounds. Firstly that it would ensure a market penetration of renewable energy technologies, and secondly that it would enlarge the number of independent power producers, an important part of privatisation (Mitchell, 1996). Prior to privatisation, UK renewable energy policy was based on R&D programmes and a few demonstration projects (Mitchell, 1995).

[35] The first NFFOs were expected to last for a contract period of at least 15 years, but following a compromise between the UK Department of Energy and the European Commission the levy was set for eight years. This meant that the capital costs had to be collected over a period of only 8 years.

[36] The levy is currently at its lowest level since it was introduced. The levy has gradually been reduced for which recent reductions was justified in order to reflect the expiry of the premium power purchase contracts under NFFO-1 and NFFO-2 which came to an end on December 31 1998.

price within each band (Mitchell, 1995). Whereas the NFFO may be deemed a success in terms of ensuring conditions for market implementation and in bringing down prices considerably, at least for wind, it seems somewhat contentious as to whether it has elicited domestic industrial developments. Some argue that the NFFO mechanism “has proved successful in stimulating the growth of a nascent industry in Britain” (Mitchell, 1996: 183), while others find that a “manufacturing industry has yet to emerge” (Hemmelskamp, 1999: 424).

That said, the British Government has proposed to introduce a ‘Renewables Obligation’ to succeed the NFFO arrangement. This obligation is set to be a major plank in the Government’s new policy requiring electricity supply companies to supply 10% of their power from renewables by 2010. The new proposal also includes an exemption of renewable-generated electricity and heat from the proposed Climate Change Levy, and an expanded new and renewable energy support programme, including research, development, demonstration and dissemination of information.

4.3.2 Renewable Portfolio Standards and Green Certificate Trading

Whereas the UK has relied mainly on the NFFO to stimulate new markets for NRE, the debate in the US has focused more on an instrument known as the ‘renewable portfolio standard’ (RPS). First introduced by the American Wind Energy Association, a RPS allows regulators to require that a certain minimum of a utility’s or state’s electricity use comes from renewable energy sources. In order to implement such a policy, a purchase requirement could be imposed on retailers (or generators depending on policy design) selling electricity to utilities or other customers. To add flexibility into such a policy, one could allow the regulated agents to trade through a system of certificates or credits. A credit thus signifies as a proof that one kWh of electricity has been generated by a renewable source, and is as such treated as a different commodity than electricity itself. The RPS thus bears similarity to tradable permit approaches to pollution control, such as the US SO_2 allowance programme created under the Clean Air Act Amendments of 1990[37], and the arrangement proposed for tradable permits (emissions trading) under the Kyoto Protocol.

In order to meet requirements, retailers could choose to construct and operate their own renewable production facilities or purchase credits on the marketplace (credit market). All decisions regarding the use of a particular fuel or technology and the price of permits are left entirely to the retailer, generator or investor. The role of the Government is restricted to that of monitoring and certifying compliance and, if needed, to penalise actors that fail to comply with the requirements. Among the potential benefits from RPS is that it provides long-term stability in terms of guaranteed markets for renewables, which may attract investors. It may also reduce transaction costs compared to other systems relying on administrative dissemination of funds. However, it may be argued that RPS would largely favour near-market technologies that represent low-cost alternatives, so that less competitive options are not supported. The same criticism is also raised against the UK NFFO (Elliot, 1996), which underlines the need to complement ‘market-pull’ policies with ‘technology-push’ strategies. So far, however, only a few states have adopted the RPS (Wiser *et al*., 1998).

At the EU level it is becoming increasingly recognised that the prevailing incentive schemes for NRE developments might not be consistent with the process of energy market liberalisation. However, removing state subsidies also poses a threat to NRE developments, which is expected to play a key role in EU efforts to curb GHG emissions. Another model designed to facilitate the integration of renewables into a liberalised market and at the same time enabling renewables to be partially compensated in terms of environmental benefits is thus being developed at the EU and member state level. Under this system of *green energy certificates*, which bears resemblance to the RPS scheme, generators of renewable energy are issued certificates they can sell separately from the electricity produced. Trading of such green certificates thus enables a renewable plant to generate extra funds for environmentally benign production. A buyer who wants to have a guaranteed purchase of renewable electricity can buy a green certificate in addition to the electricity bought through the grid from regular suppliers. A *voluntary* green certificate market was introduced in the Netherlands in 1998, whereas Denmark has opted to introduce a system in which all consumers are *obliged* to buy a

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[37] See e.g. Tietenberg (1995), McLean (1997) or Burtraw (2000) for discussions of goals, results and lessons

certain share of electricity generated by renewables (Morthorst, 2000). Similar arrangements have been proposed by a number of EU member states, whence awaiting the finalisation of the contentious Directive on renewable energy support[38]. In brief, both RPS and green certificate trading schemes comprise a kind of hybrid instrument, in the sense that they combine the use of economic instruments (trade) with standards (minimum supply levels of NRE). Moreover, and most importantly, they create markets that reduces the risks of investing in the development and deployment of NRE technologies.

4.3.3 Green power marketing

Unlike systems relying on public efforts to establish markets for NRE, the principle of ‘green power marketing’ takes advantage of customer’s willingness to pay a premium for products that provide environmental and/or private benefits. The term ‘green power’ generally refers to electricity supplied from renewable energy sources. In electricity systems that are open to competition, green power marketers may thus offer green products and services to residential, commercial, and wholesale customers. Green power marketing has thus the potential to expand markets for renewable energy in terms of enhancing availability of renewable options. In the US more than 50 utilities in 18 states have either developed or intend to develop programs for green power. By August 1999 some 55MW of renewable energy capacity had been developed through such programs, with an additional 20 MW expected by the end of the year (Swezey and Bird, 1999). Among other countries that have implemented such voluntary trading schemes we find the Netherlands, Sweden, Norway, Canada and Ireland.

In sum, this chapter has identified and assessed a selection of policy instruments in terms of their ability to support the development and deployment of new technologies, and to some extent the creation of new (niche) markets. However, it follows from the discussion that none of these instruments are in themselves likely to be sufficient for technological change and innovation to result. The analysis rather suggests that a comprehensive and innovation-

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learned on the basis of the US experience with SO_2 allowance trading.

[38] Following a pan-European voluntary initiative involving energy companies and organisations in Denmark, the Netherlands, Sweden, Norway, Greece and Italy, trading of renewable energy certificates will in fact start on January 1 2001. The test phase is slated to last 18 months, according to the Renewable Energy Certificates System (RECS) secretariat (Reuters Environmental News Service, http://www.planetark.org, [14.12.2000]).

oriented policy should comprise a blend of these instruments in order to make justice to all stages of technological change; i.e., a combination of ‘technology-push’ and ‘demand-pull’.

5 Towards an innovation oriented policy framework: A template for public policy assessment

The basic premise in this report is that moving from a carbon-intensive to a low-carbon or 'climate-friendly' future will require profound technological innovation and shifts from carbon-intensive to low-emitting energy sources. The challenge of avoiding or mitigating the adverse impacts of global climate change presents policymakers with difficult choices in terms of curbing GHG emissions without knowing exactly how the future will unfold. Uncertainty is also due to the fact that a large number of technologies have the potential for emissions abatement. Thus, in order to be useful and help policymakers in finding the right blend or portfolio of instruments, the aim of the analytical framework proposed in this chapter is to accommodate complexity, while also bringing order to it.

Recognising the real-world complexities and uncertainties involved in technological innovation processes, and that it is inherently difficult to assess the dynamic efficiency properties of policy packages *ex-ante*, providing policy prescriptions is as dangerous as it is tempting. Moreover, our understanding of the factors and mechanisms that promote and sustain the processes of technological change and innovation is still incomplete. That said, the foregoing discussion points to certain key factors and 'lessons' that should be taken into account by policy makers when formulating strategic policy objectives and selecting and policy instruments to promote technological innovation.

Firstly, drawing upon the stylised typology of technological change in section 2.1 and the assessment of policy instruments in chapter 4, policymakers are unlikely to find or develop a single-best instrument or 'common panacea' to facilitate and promote technological innovation. Rather, the creation of new products and markets necessitates a combination of 'technology-push' and 'demand-pull' strategies.

Secondly, policymakers should recognise that selecting policies and targets solely within the context of *current* knowledge of costs and trends may not allow for reaping the full benefit of technological innovation; e.g., actualise dynamic efficiency gains. As argued in sections 2.1 and 3.2, economists have traditionally used models in which technology is treated as an *exogenous* addendum to the economy, for which certain assumptions are made regarding future improvements in technical performance and costs[39]. Rather than making explicit assertions of how the future may unfold, and particularly to the extent that radical or ‘system transformative’ development trajectories are called for, a key task for policy action is to establish framework conditions conducive to guiding and co-ordinating innovation processes in *new* and environmentally benign *directions*. For instance, in order to support and facilitate the transformation of the currently fossil fuel dominated energy system into one that includes a larger share of cleaner and new renewable energy technologies, one needs to improve upon a number of elements. Such efforts may involve strengthening the competence and skills of key actors, establishing bridging institutions and networks conducive to supporting the deployment and dissemination of new knowledge and competence, and creating (niche) markets to facilitate the inclusion of new technologies for energy production and consumption.

Thirdly, policy design should take into account that technologies are selected not only on the basis of technical or economic performance measures, but also by prevailing socio-political and cultural norms, rules and preferences (see section 2.4). Owing to the embodiment of technologies in a larger socio-economic context and the responsiveness of technological change to politics and culture, policies should be capable of overcoming various kinds of barriers and inertia. If not properly addressed by policymakers, such impediments may prevent society from reaping the full benefits of new technologies.

Finally, as discussed in chapters 3 and 4, policymakers need to critically examine and understand the mutual *interplay* between public policy and technological innovation. For instance, climate and innovation policies are inextricably linked, in terms that the one may reinforce and improve upon the conditions for the other. Hence, technological innovation may facilitate the refinement of policy and targets and allow for the introduction of more ambitious and far-reaching environmental targets, at least in the long-term, whereas the effectiveness of public policy clearly hinges on their impact on technological innovation[40]. Exploiting such

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[39] Models assuming endogenous technological change; i.e., that technology forms and develops within rather than outside the economy, are also developed and used.

[40] A relevant example in this respect is the contentious debate on natural gas fired power in Norway. The previous centrist government argued strongly that allowing for gas-fired power production based on ‘conventional’ technologies would jeopardise Norway’s commitments under the Kyoto protocol. However, in a medium to long-term perspective, the government would not preclude the future use of gas power in

synergies is important not the least as it is found that a large number of environmental innovations origin outside the regulated sector, and often for reasons other then improving environmental performance as such (e.g., Kemp, 2000).

5.1 The policy challenge of combining ‘push’ and ‘pull’

Even though ‘linear’ stimuli-response models of technological change (‘push-pull’) do not adequately represent endogenous mechanisms and non-linear effects arising from learning, feedbacks and increasing returns, it is nevertheless crucial to apprehend the interplay between demand and supply-side logic as they pertain to ‘upstream’ and ‘downstream’ activities. The former embraces the creation of new products and processes (invention), for which publicly funded R&D (basic and applied research) represents a core instrument. The latter is fundamentally oriented towards instruments that facilitate deployment and dissemination of new technologies in niche- and competitive markets, thus capturing the phases of innovation and diffusion. The aggregated complex of technological change is thus affected by the opportunity and appropriability conditions created by the economy for firms and individuals to capitalise on investments in research, development, demonstration, deployment, and dissemination (RD^4) of new technologies. If policy makers fail to recognise the innate and strong couplings between technological (‘push’) and market opportunities (‘pull’), the effects of policy action aimed at encouraging technological innovation may be significantly weakened[41].

In order to create incentives for investments in (environmentally benign) innovation, policymakers should seek to co-ordinate environmental and economic goals through a policy framework consisting of three categories. First, a ‘technology push’ may be induced by *direct* public funding for RD&D, as well as by *indirect* means to provide incentives for private sector investment in research and development, such as tax incentives/credits and rebates. Secondly, ‘demand pull’ could be spurred through instruments aiming to bring new technologies to the market place and ensure (widespread) dissemination. Thirdly, public

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Norway in the advent of so-called ‘emissions-free’ technologies. Hence, in the eyes of policymakers, compliance with environmental goals was clearly made dependent on technological innovation.

[41] See Loiter and Norberg-Bohm (1999) and Norberg-Bohm (2000) for a timely evaluation of public policies to stimulate environmentally enhancing technologies in the US.

policies may establish or enhance effective channels for sharing of knowledge and information and capacitate learning (technological, organisational) in order to improve accessibility and utility of research results. Network/capacity building and ensuring feedback from users and customers are in this respect crucial in order to make further technological, environmental and economic improvements and to broaden fields of application.

These observations imply that a long-term and comprehensive strategy should include a portfolio of carefully selected instruments and actions that does justice to the different stages of technological change. Such a strategy may include ambitious and long-term targets, continuous monitoring of policy outcomes and impacts, and the creation of facilitating and adaptive environments for learning about new technologies and their applications. For instance, using a combination of ambitious portfolio standards and economic instruments could be useful to the extent that it combines effectiveness with a conception of direction and potential for radical (systemic) technological change. Moreover, explicitly rather than implicitly incorporating concerns for innovation may facilitate a development from a re-active (adaptive) towards a pro-active (preventive) climate policy.

That said, stringent policies are clearly not the only stimulus for innovative action at the level of the firm, which often develops and adopts environmental technologies for purely commercial reasons conducive to cost-savings or quality improvements. Moreover, unplanned events and technological ‘surprises’ may also come into play, in a way that changes the rate and direction of technological change. Nevertheless, it seems evident that a template for dynamic efficiency assessments should be firmly based on the recognition that public policy and governmental intervention may affect both the *rate* and *direction* of technological innovation. It is also crucial that public policies support and facilitate network and capacity building, for example through user-supplier interactions, so that network effects enhance rather than obstruct the evolution of new technologies.

5.2 Introducing fuzzy-set analysis for policy impact assessments

Drawing upon the preceding analysis, this section aims to develop a process- or arrival-oriented analytical framework that allows researchers to exploit and assess the linkages between the choice of policy instruments and technological innovation. The objective is to provide a ‘tool’ that combines the interpretative understanding offered by case-oriented approaches, in-depth analysis of a selected number of cases and ‘holistic’ understanding of each case, with a more theoretically founded understanding of the factors and mechanisms that shapes specific patterns of technological change.

5.2.1 Simplified template: 3´3 example

Table 2 presents a stylised and simplified template for policy assessment that explores linkages between a selected range of policy instruments (independent variables) and relevant stages of the technological innovation process (dependent variables). For reasons of simplicity and ‘educational’ purposes, we consider first an example involving only three instruments and three stages. Note that the template comprises a subset of the threefold typology of public policy instruments discussed in chapter 4 (information is omitted) and the typology of technical change presented in section 2.1. The purpose is simply to use the 3×3 template as an illustration of whether, and if so to what extent selected policy instruments - direct regulation (e.g., standards), economic instruments (e.g., taxes) and R&D support - affect the stages of *invention, innovation, and diffusion*.

The template is in principle based on Boolean algebra, which provides an explicit algebraic analysis for qualitative comparison (e.g., Ragin, 1987). However, as Boolean algebra in its basic form is limited to binary data and two conditions - true (or present) and false (or absent) represented by 1 and 0, respectively - we augment the ‘in or out analysis’ by the introduction *degrees of membership* (Ragin, 2000). Besides the two qualitative states (crisp sets) of full membership (1) and full non-membership (0), fuzzy sets permit in principle the state (dependent) variables to take on any value between these states.

However, the use of fuzzy sets in this work differs somewhat from the way it is applied by Ragin (2000), in which fuzzy membership scores are used to “indicate the degree to which relevant cases … belong to the sets that social scientists use to describe and analyse them” (ibid.: 118). The notion of ‘degree of membership’ is typically used in explaining causal relationships between factors and outcome, in the form of is “x” important for “y”. In this work fuzzy sets are used in an “arrival” or process oriented sense, for which scores between 0 and 1 indicates the degree of *impact* that an independent variable has on a dependent variable. Impact denotes in this respect the potential “effect” of a specific policy instrument on a specific stage in the technological innovation process. For reasons of simplicity we restrict the population of possible states to a fuzzy set consisting of five discrete states; i.e., {0,0.25,0.5,0.75,1}. A set-score of 0 is used to indicate little or marginal impact, whereas scores in the range 0.25 to 1 indicates the degree of positive impact. As the set-scores provide an indication of the dynamic efficiency properties of a given policy strategy, the matrix is denoted 'Dynamic Efficiency Matrix' or *DEM*. Note that it is also assumed that any policy instrument may have multiple impacts, i.e., affect several stages.

In order to assign the individual set-scores as indicated in Table 2 we draw upon the conceptual discussion of specific stages in the technological innovation process (section 2.1) and the assessment of policy instruments in chapter 4. However, let it be said that the assignment of set-scores is done somewhat loosely. In any rigorous analysis, one would have to use set scores that have been carefully calibrated using substantive empirical evidence from case studies and theoretical knowledge. The example in Table 2 is thus mainly used for illustrative purposes.

R&D support is here assigned as the instrument best suited to stimulate the creation of a new idea, new knowledge or a novel technical design (*invention*) through the processes of 'trial and error' and basic research, hence a set-score of 1. However, regulation and economic instruments may also have some impact on R&D efforts in the private sector, hence a value of 0.25[42]. As regards the practical implementation or marketable adoption of new knowledge and technologies (*innovation*), direct regulation and economic incentives may provide the leverage for innovation by means of mandating the use of new technologies ('technology-forcing' standards) or financial incentives for their adoption (charges, tax-brakes). Since the *extent* to which regulation stimulate innovation is uncertain (see section 4.1), and decisions to adopt new technologies depend on the level/size of economic means (e.g, tax-level), they are both assigned scores of 0.5, which constitutes the *crossover* point (Ragin, 2000). R&D support may have some effect on innovation to the extent that it supports deployment of technologies through applied research or development projects – hence a score of 0.25.

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[42] One may also find that innovation or diffusion oriented policies provides incentives for R&D activities by means of providing motivation and securing markets in which new technologies will be demanded.

When it comes to the dissemination of new technologies in a wider array of markets (*diffusion*), direct regulation may be effective in terms of imposing mandatory future market shares (‘forced diffusion’). Economic incentives could on the other hand reduce adjustment costs or raise the benefits (‘induced diffusion’) of adopting new technologies. Both instruments are assigned *crossover* scores of 0.5, whereas the dissemination of *knowledge* about new technologies yields R&D support a score of 0.25.

Table 2: Simplified representation of the interplay between policy instruments and technological innovation - 3×3 Dynamic Efficiency Matrix.

	Direct regulation	Economic instruments	R&D support
Knowledge creation (*invention*)	0.25	0.25	1
Technology and knowledge application (*innovation*)	0.5	0.5	0.25
Technology and knowledge *diffusion*	0.5	0.5	0.25

This mechanistic representation of the innovation effects of policy instruments could also be formulated as a linear transformation, i.e.:

$$\begin{pmatrix} s_1 \\ s_2 \\ . \\ . \\ s_n \end{pmatrix} = DEM \times \begin{pmatrix} p_1 \\ p_2 \\ . \\ . \\ p_m \end{pmatrix}, \; DEM = \begin{bmatrix} 0.25 & 0.25 & 1 \\ 0.5 & 0.5 & 0.25 \\ 0.5 & 0.5 & 0.25 \end{bmatrix}$$

where $s_1, s_2, \ldots, s_n$ is a vector representing the stages in the technological innovation process and, DEM the dynamic efficiency matrix and $p_1, p_2, \ldots, p_m$ a vector of policy instruments.

5.2.2 Augmented template: 7´7 example

Table 3 presents an augmented version of the 3×3 *DEM* in Table 2. Firstly, the matrix provides a more comprehensive representation of technological innovation processes, including also the stage of *niche market creation* as well as key mechanisms concerning *economies of scale*, *learning* and *network and capacity building*. Even though these three mechanisms is not related to a specific 'stage' in the technology development cycle, they are included in terms of their capacity to create and sustain functioning markets and facilitate cost reductions through learning and scale-effects. Moreover, they also address the need to complement improvements in economic or technical performance with innovations at the organisational or institutional level through network and capacity building (see section 5.1)[43]. Secondly, four additional policy instruments is added so that the template constitutes a 7×7 *DEM*.

The assignment of set-scores in Table 3 follows the somewhat 'loose' logic of the 3×3 example presented in the previous section. The following gives some explanation for the assignment, with the scores indicated in brackets for each additional policy instrument. Information & education (I&E) is assumed to have only minor impact on creating niche markets and economies of scale, but some effect (0.25) on invention by means of disseminating knowledge about technologies and market opportunities that could spur further R&D investments. The impact of informing and educating is assumed to be somewhat stronger as regards the adoption (innovation) and diffusion of new technologies, hence a crossover score of 0.5. Demonstration programmes (DP) may also facilitate the adoption of new technologies (0.5) and provide some leverage for the development of niche (nursing or bridging) markets (0.5). Establishing such programmes could also allow organisations and individuals to gain experience with new technologies, and thus stimulate learning (0.5). Public procurement works in similar ways as DP, but could have a more direct effect on the market for new technologies and thus diffusion through government purchases. Such effects are clearly evident in the cases of public programmes aimed at solar photovoltaics, such as the U.S. "Million Solar Roofs initiative", the Japanese "New Sunshine" project and German's

"1000 Rooftop Program". As shown in Table 3, it is assumed that obligations, such as renewable portfolio standards, have the biggest impact on the creation of new niche markets (0.75) and diffusion (1.0) by way of establishing mandatory standards for future market shares of new technologies. By stimulating demands for new technologies, economic instruments and obligations could also stimulate lower cost supply in the medium term through economies of scale, hence the high scores of 1.0 and 0.75 in this category.

Table 3: Extended representation of the interplay between policy instruments and technological innovation - 7×7 Dynamic Efficiency Matrix.

	Direct regulation	Economic instruments	Information & education	R&D support	Demonstration programmes	Public procurement	Obligation (RPS)
Knowledge creation (*invention*)	0.25	0.25	0.25	1	0.25	0.25	0.25
Technology and knowledge application (*innovation*)	0.5	0.5	0.5	0.25	0.5	0.5	0.5
Creating niche markets	0.5	0.5	0	0	0.5	0.5	0.75
Technology and knowledge *diffusion*	0.5	0.5	0.5	0.25	0.25	0.75	1
Social and institutional learning	0.5	0.5	0.5	0.75	0.5	0.25	0.5
Economies of scale	0.5	1	0	0.25	0.5	0.5	0.75
Network and capacity building	0.25	0.25	0.5	0.5	0.25	0.25	0.25

Even though the 7×7 *DEM* provides a relatively detailed account of the interplay between policy instruments and innovation, it still gives a coarse representation of the technological innovation processes and the incentive structures pertaining to the different policy

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[43] See Jacobsson and Johnsson (2000) for an analysis of ways in which networks may facilitate and promote technological change and innovation, for instance by increasing the knowledge base of individual firms,

instruments. For instance, the *DEM* aggregates the effects of a large group of economic instruments, which may include tax credits, investment or production subsidies, effluent charges, emissions trading, etc. These instruments may indeed have dissimilar effects on different stages in the technological innovation process, and thus different impacts on dynamic efficiency. The same applies to different kinds of direct regulations, in terms that technology or performance based standards may be designed and implemented with the objective of facilitating either innovation or diffusion, or both. That said, these deficiencies pertain mostly to the level of detail rather than the analytical framework as such. Hence, one might increase the level of detail and comprehensiveness by extending the number of instruments and/or stages in the technological innovation process. A more detailed assessment of the scope and limitations is given in section 5.4.

5.3 Guidelines for dynamic efficiency assessments: Introducing the notion of “pathways”

A brief glance at Table 3 suggests that the dynamic efficiency properties of public policies depend on simultaneously investing public resources in R&D activities and creating a market for adoption and diffusion of new technologies. Both ‘technology-push’ and ‘demand-pull’ are thus portrayed as key determinants for technological innovation to result. Moreover, and quite interestingly, the template illustrates that there are in fact several combinations of instruments or ‘pathways’ that satisfy the requirements of an all-inclusive strategy; i.e., strategies that encompass all stages in the technological innovation process from knowledge creation towards widespread dissemination of new technologies and economies of scale.

Before discussing and assessing different policy strategies and possible ‘pathways’, note first that not all combinations of instruments are viable. This is particularly so when the number of instruments grow, for which the potential of conflicts or detrimental interaction between instruments increase. For this reason there might be circumstances under which two or more types of instruments might or should not be employed simultaneously to address the same problem or ‘issue area’. For instance, using direct regulations for pollution control (emission standards) could be incompatible with the use of certain types of economic instruments such

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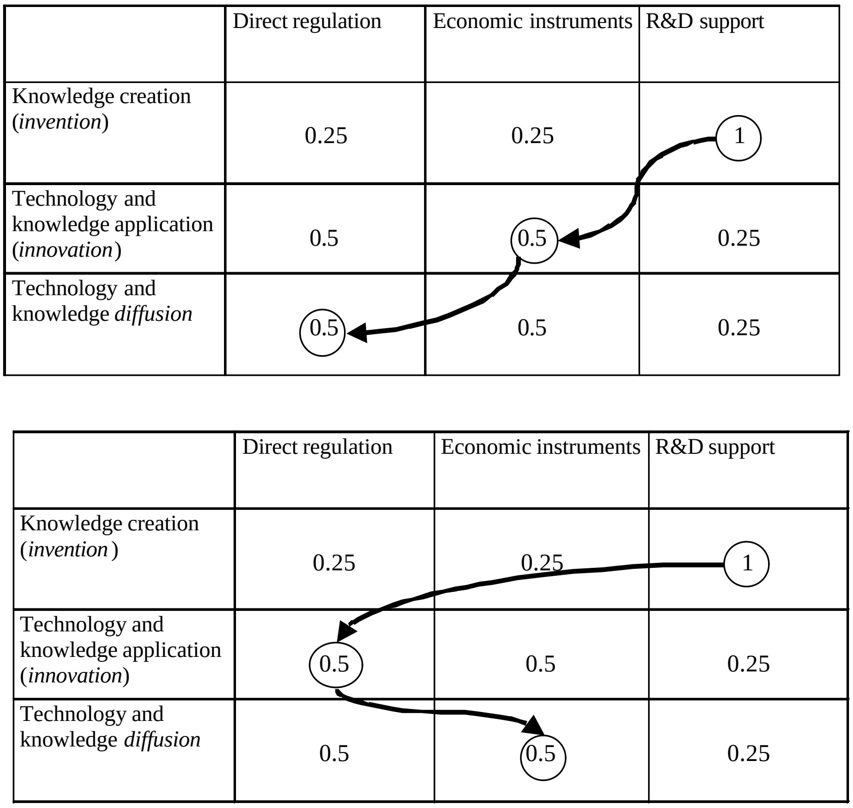
compensating for limitations in firms’ search spaces, and remove institutional constraints to company growth.

as effluent charges or emissions trading. Second, different instruments could be, and are in practice often applied for different purposes and at different stages in the technology development cycle. R&D subsidies may typically be applied to provide the leverage for knowledge creation and application, whereas emissions trading schemes are designed partly to prevent emissions from exceeding a certain level.

In the following we also introduce and use the concept of 'all-inclusive' policy strategies, meaning ones that include a set of policy instruments that affect all stages in the technological innovation process; e.g., combine technology-push with demand-pull. Such strategies may be identified in terms of 'pathways' that traverse through entries in the *DEM* with a score of 0.5 or higher, where 0.5 is the *crossover* point. Similarly, a 'non-inclusive' strategy is used in reference to combinations of policy instruments that fail to affect all stages.

5.3.1 Qualitative assessments

A *qualitative* assessment of the simplified 3×3 *DEM* in Table 2 reveals the existence of two 'all-inclusive' strategies that make use of *all* three instruments. The two pathways are shown in Figure 1, in which one option is to use R&D support to facilitate the creation of new knowledge and technical options (invention). Some form of direct regulation and economic instruments may then be applied to support adoption (innovation) and dissemination (diffusion) of the technology at the market place, respectively. Note, however, that there are also two 'all-inclusive' strategies that make use of only two instruments, in which R&D support is combined with either direct regulation or types of economic instruments.



	Direct regulation	Economic instruments	R&D support
Knowledge creation (*invention*)	0.25	0.25	1
Technology and knowledge application (*innovation*)	0.5	0.5	0.25
Technology and knowledge *diffusion*	0.5	0.5	0.25

	Direct regulation	Economic instruments	R&D support
Knowledge creation (*invention*)	0.25	0.25	1
Technology and knowledge application (*innovation*)	0.5	0.5	0.25
Technology and knowledge *diffusion*	0.5	0.5	0.25

Figure 1: ‘All-inclusive’ policy strategy and pathways for 3×3 example

Even though viable (‘all-inclusive) strategies in the 3×3 example is easily ‘found’ by means of simple inspection, the problem may also be approached in a more systematic and comprehensive manner. This is particularly important as the number of instruments grows and a more detailed representation of the technological innovation process is used. One option is to approach the problem using the framework of mechanistic model building and mathematical programming. In order to create a mathematical representation of the problem complex we introduce variables $s_1,s_2,\ldots,s_n$ representing the stages in the technological innovation process and $p_1,p_2,\ldots,p_m$ the number of policy instruments. Consider here the 3×3 *DEM* in Table 2, for which we may display the *occurrence* or *incidence matrix* as shown in equation (2)[44]. Entries in the matrix denoted by x’s in row i (stage) and column j (instrument) indicate a set-score of 0.5 or higher:

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[44] See e.g. Westerberg (1979) or Williams (1993)

$$\begin{array}{cccc} & p_1 & p_2 & p_3 \\ s_1 & & & x \\ s_2 & x & x & \\ s_3 & x & x & \end{array} \qquad (2)$$

The task of identifying every ‘all-inclusive’ strategy policy assessment could then be solved as an *assignment problem*, for which the objective is to allocate a certain number of policy instruments from the portfolio of size *m* to the *n* stages of technological innovation, subject to a set of constraints[45]. The most efficient algorithm for this task is the Hungarian method (Williams, 1993: 85).

Another variant of the problem is that of finding the *minimum* number of policy instruments required in an ‘all-inclusive’ strategy. This problem may be formulated as finding the ‘shortest path’ connecting all the stages from invention to diffusion, i.e. from S_1 to S_3. A simple inspection of equation (2) reveals two ‘all-inclusive’ strategies consisting of two policy instruments, in which R&D support is combined with either direct regulation or economic instruments. Another, possibly banal yet vital, conclusion that can be drawn is that R&D is *necessary* but not *sufficient* for innovation and diffusion to result.

Yet a third alternative is to obtain the combination of instruments that ‘maximise’ the impact on technological innovation; i.e., the strategy that gives the largest dynamic efficiency gains.

Whereas the qualitative assessment of the 3×3 *DEM* proved rather simple, the task is a lot more complex when it comes to the extended 7×7 *DEM* in Table 3. A simple inspection reveals the existence of several ‘all-inclusive’ policy strategies, including various combinations of economic instruments, information & education, R&D support, demonstration programmes, public procurement and obligations such as portfolio standards. One example of an ‘all-inclusive’ pathway, in which we allow for a single policy instrument to affect two or more stages in the innovation process, is illustrated in Figure 2.

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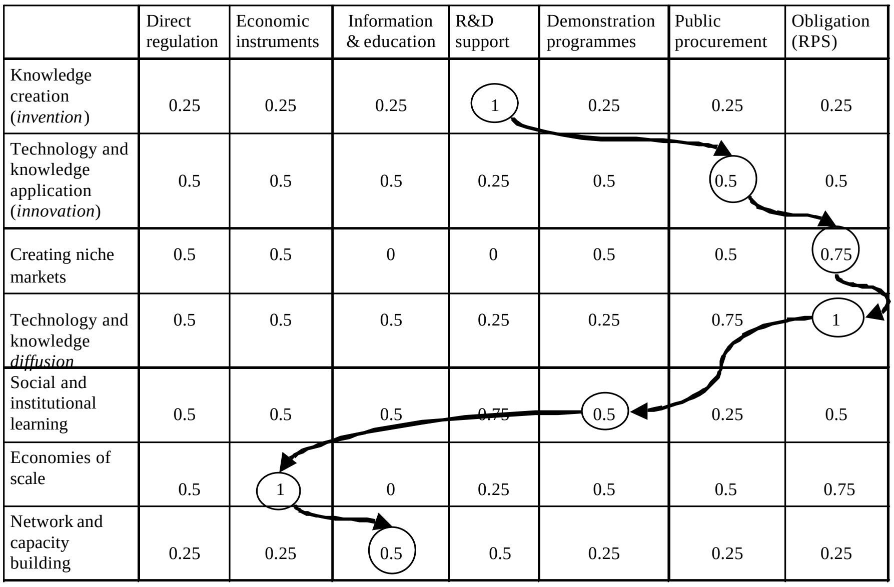
[45] Note here that the problem may be square, over- or underdetermined, in that the number of policy instruments (*n*) may be equal to, larger or smaller than the number of stages (*m*).

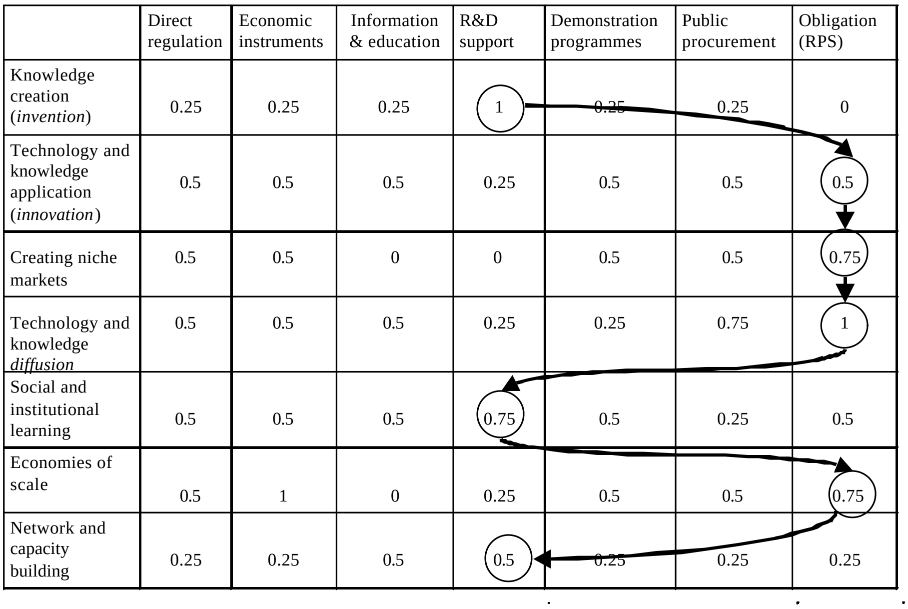


	Direct regulation	Economic instruments	Information & education	R&D support	Demonstration programmes	Public procurement	Obligation (RPS)
Knowledge creation (*invention*)	0.25	0.25	0.25	1	0.25	0.25	0.25
Technology and knowledge application (*innovation*)	0.5	0.5	0.5	0.25	0.5	0.5	0.5
Creating niche markets	0.5	0.5	0	0	0.5	0.5	0.75
Technology and knowledge *diffusion*	0.5	0.5	0.5	0.25	0.25	0.75	1
Social and institutional learning	0.5	0.5	0.5	0.75	0.5	0.25	0.5
Economies of scale	0.5	1	0	0.25	0.5	0.5	0.75
Network and capacity building	0.25	0.25	0.5	0.5	0.25	0.25	0.25

Figure 2: Pathway illustrating an ‘all-inclusive’ and comprehensive policy strategy

Subjecting Figure 2 to a more detailed analysis calls for a few remarks. First, even though the direction indicated by the arrows depict a pathway leading from knowledge creation (first stage) to network and capacity building (final stage), this should not be taken as arguing that an ‘optimal’ technological development trajectory evolves along a strictly defined path. Nor is it argued that the portfolio of policy instruments should be introduced in the particular sequence indicated in the figure. The purpose is rather to portray a policy strategy that encompasses all stages in the development cycle of new technologies.

Second, the timing of introduction and co-ordination of policy instruments is clearly a complex and difficult task that depends, *inter alia*, on the maturity and availability of the technology in question or the extent to which network effects are likely to enhance or constrain its adoption and diffusion. Third, identifying all ‘all-inclusive’ pathways, in particular for large systems, is indeed a complex problem that requires appropriate (rigorous) mathematical (algorithmic) techniques. A discussion on appropriate techniques and solution methods is, however, beyond the scope of this report.



	Direct regulation	Economic instruments	Information & education	R&D support	Demonstration programmes	Public procurement	Obligation (RPS)
Knowledge creation (*invention*)	0.25	0.25	0.25	1	0.25	0.25	0
Technology and knowledge application (*innovation*)	0.5	0.5	0.5	0.25	0.5	0.5	0.5
Creating niche markets	0.5	0.5	0	0	0.5	0.5	0.75
Technology and knowledge *diffusion*	0.5	0.5	0.5	0.25	0.25	0.75	1
Social and institutional learning	0.5	0.5	0.5	0.75	0.5	0.25	0.5
Economies of scale	0.5	1	0	0.25	0.5	0.5	0.75
Network and capacity building	0.25	0.25	0.5	0.5	0.25	0.25	0.25

Figure 3: Pathway illustrating a ‘minimum set’ policy strategy

On this account, the analytical framework represented here is useful first and foremost as a tool for examining the ‘innovation potential’ of a given policy and for qualitative *comparative* policy analyses. In order to demonstrate its usefulness, examining the template in Table 3 also suggests a possible ‘minimum set’ as illustrated in Figure 3, which includes only R&D support and obligations, for example in terms of portfolio standards or certificate trading.

5.3.2 Quantitative assessments

In order to use the analytical framework for *quantitative* assessments, one could in principle obtain an index of the *dynamic efficiency properties* by adding the scores for a given combination of policy instruments. By allowing a single policy instrument to have an effect on several stages in the technological innovation process, such an index may be obtained by summation:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} S_i P_j \qquad (3)$$

where S_iP_j denotes the individual entry (score) in column i and row j of the Dynamic Efficiency Matrix (*DEM*), m the number of selected policy instruments, and n the number of stages in the technological innovation process.

Alternatively, one could choose to add only entries with scores higher than the *crossover* point (0.5), in which case the set-score (dynamic efficiency index) is given by:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} S_i P_j \, , \forall S_i P_j \geq 0.5 \qquad (4)$$

In order to provide a numerical example we may compare the 'all-inclusive' strategy in Figure 2, which consists of a portfolio of six policy instruments, with the 'minimum-set' strategy in Figure 3, including only two instruments. Using equation (3) gives set-scores of 18.0 and 6.75, respectively, whereas equation (4) gives set-scores of 15.0 and 5.75. Based upon this quantitative assessment one would conclude that the 'all-inclusive' policy strategy is the preferred in terms of *dynamic efficiency properties*.

5.4 Scope and limitations of the proposed analytical framework

The analytical framework presented here in terms of the Dynamic Efficiency Matrix (*DEM*) could offer a useful tool or 'focusing device' for comparative policy analysis and empirical investigations. It allows the researcher to (i) examine the dynamic efficiency properties for different combinations of policy instruments (*ex-ante* assessments), and (ii) evaluate different outcomes in relation to a selected set of policies and measures (*ex-post* analysis)[46]. Hence, a 'non-inclusive' and/or 'low-score' policy strategy might be indicative of or (partly) explain poor technology and industrial development dynamics, whilst a 'high-score' and/or 'all-inclusive' strategy might elucidate reasons behind success stories. Moreover, by expanding the empirical research base and testing/validating the framework against selected case studies, the researcher may gradually improve upon and refine the qualitative and quantitative assessments.

However, the objective is not primarily to isolate or causally link the effects of particular policy instruments on different stages in the innovation process, in terms that the outcome should be accounted for as combined effects of several instruments as well as factors outside the public policy domain. Moreover, any conclusion should certainly take into account a number of limitations and potential caveats in the framework.

5.4.1 Qualitative assessments

When using the template proposed here for *qualitative* comparative policy analysis, one should make provisions so as to correct for or calibrate assessments - *ex-ante* and *ex-post* - against the impact of other, possibly more important forces. Such forces could emanate and act from within (endogenous) as well as outside (exogenous) the system boundaries. Thus, it is widely recognised that technological innovation constitutes a set of complex and heterogeneous processes in which several factors and mechanisms influence the outcome.

Firstly, it is crucial to recognise that public policy is but one of many factors promoting, or hindering technological innovation. Many technologies with environmental benefits are furthermore often developed and adopted for purely commercial or reasons other than improved environmental performance as such. Thus, public policies may in some cases provide the leverage for innovation to result, whereas the (mere) threat of regulation or technological ‘surprises’ might be more important in other cases (e.g, Kemp, 2000).

Secondly, technological development patterns are commonly shaped in a complex interplay of supply and demand factors, such as specific national or regional circumstances, technological opportunities, ‘policy style’, market structures and appropriability conditions (e.g., Eikeland *et al*, 1999). Hence, different countries and/or sectors could, and possibly should select a portfolio of instruments that reflects idiosyncrasies (objectives and constraints) pertaining to that specific country or sector.

Thirdly, the framework at hand does not explicitly address the ‘timing’ or co-ordination of policy instruments, which requires close scrutiny by policymakers before implementing policy strategies to harness dynamic efficiency gains. It has for example been recognised that ‘technology-push’ appears to have a greater effect at the start of the technology life cycle, whilst demand-pull (market opportunities) exerts a stronger influence in stages later on (Coombs *et al*, 1987). Hence, policymakers needs to assess the maturity of the technologies in question before deciding how much effort and financial support should be allocated to for instance R&D, and, if needed, what instruments should be used to create and sustain the

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[46] See Christiansen (2000b) for a discussion of *ex-ante* assessments and *ex-post* evidence in relation to a single policy instrument, applied in a study of impacts of CO_2-taxes on environmental innovation (dynamic efficiency gains) in the Norwegian petroleum sector.

development of (niche) markets. Moreover, in cases of increasing returns and lock-ins, the allocation problem may exhibit multiple equilibria (Arthur, 1989). In such cases “steering an economy with positive feedbacks so that it chooses the best of its many possible equilibrium states requires good fortune and good *timing* – a feel for the moments at which beneficial change from one pattern to another is most possible. Theory can help us identify these states and times. And it can guide us [policymakers] in applying the right amount of effort (not too little but not too much) to dislodge locked-in structures” (Arthur, 1990: 99).

Fourthly, one should keep in mind that a key to selecting an appropriate blend of measures is to understand how the instruments *interact*. Such interaction can be harmful or beneficial, and to avoid adverse impacts and conflicts it is essential that policymakers assess the potential for interactions before implementing new policy strategies. For instance, investing public finances in RD&D could become ‘fruitless’ unless combined with instruments conducive to stimulating and sustaining the adoption and diffusion of new technologies at the market place[47]. The analysis of new renewable energy developments in Norway in section 6 provides empirical evidence on such conflicts. Moreover, there may also be circumstances under which assumed cost-effective instruments undermine potentials for dynamic efficiency gains. For instance, emissions trading or portfolio standards may fail to provide incentives for investments in technologies that are not (yet) cost-effective, which consequently may constrain the long-term development of new and cleaner technologies, such as new renewable energy technologies. Policymakers should thus recognise that it is the whole portfolio of instruments, the mutual interaction between instruments, and their interplay with other societal process that in sum determines whether or not a policy strategy is capable of facilitating the adoption and widespread dissemination of environmentally benign technologies.

5.4.2 Quantitative assessments

Similarly, great, or even greater care should be taken before affirmative conclusions can be drawn on the basis of *quantitative* assessments. Firstly, the deterministic and mechanistic

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[47] Smith and Sorrell (2001) provides an assessment of interaction between carbon emissions trading and the EU Integrated Pollution Prevention and Control (IPPC) Directive, while Morthorst (2001) discusses interactions between a market for tradable GHG-permits and a green certificate market to promote the development of renewables.

representation of the *DEM* does not explicitly take into account the *level* of support offered by each of the policy instruments. For instance, it does not explicitly address what is an appropriate or even ‘optimal’ level of publicly funded R&D to induce development of new products or processes. Secondly, the framework does not address the questions of *co-ordination* and *duration*, in terms of when and for how long combinations of different instruments are or should be used[48]. Striking the right balance hinges to some extent on the relative importance of ‘demand-pull’ versus ‘technology-push’ for different stages in the innovation process; i.e., whether market or technological opportunities yield the ‘best’ incentives. Thirdly, it is by no means clear how to define the target or objective for different (combinations of) instruments. For example, how should one assign an appropriate target for obligations under a certificate trading system, and how does the assigned target affect the level of publicly funded R&D? Owing to the complex interplay between different policy instruments it could be that a carefully designed and balanced ‘minimum set’ strategy yields higher dynamic efficiency gains (technology and industrial development dynamics) than an ill-conditioned strategy including a broader portfolio of instruments.

Against this backdrop, the next section elaborates some more on the context and policy framework in which different instruments are set to operate.

5.5 Context and barriers

Besides comprehending the ways in which policy design and ‘style’ affect different stages in the development cycle of technological change, one should bear in mind that the codes of successful innovation can only be deciphered by studying and understanding the interplay between technical, commercial, social and institutional spheres. Any assessments of the interplay between policy instruments and technological innovation (dynamic efficiency) should take into account the opportunity structures and constraints specific to the country, region or sector being studied.

A recent study on *green energy-industrial innovation* in Northern European countries reveals that the ‘greening’ of industry is indeed a complex process that typically involves changes in

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[48] Christiansen (2000b) provides a discussion on the (perceived) ‘staying power’ of policy instruments and its impact on technological change and innovation in the Norwegian petroleum sector.

production systems and consumption patterns, institutional change, and changes in social and political practices (Eikeland *et al*, 1999). A key observation is that the six case studies included in the study display highly different patterns of political and commercial dynamics. Empirical evidence showed that the energy-industrial innovation processes may be either predominantly politically/socially or commercially/industrially initiated. For instance, the development of a world-leading wind power industry in Denmark and increasing market shares for wind power in domestic power generation, were partly caused by public programmes for fuel conversion and substantive subsidies, and partly by the involvement and strong support from the farming interest segment (ibid.: 332). Another issue highlighted by the study was the *multilevel* interplay and complex dynamics between processes at the local, national and international level, pertaining to market behaviour, technology, political decision making and social anchoring.

Another key issue affecting technology development dynamics is the presence of various kinds of impediments, such as market barriers, network externalities, or other sources of inertia and ‘lock-in’ (technological and institutional) that may constrain the evolution of new technologies and undermine the effectiveness of public policies. In order for new technologies to successfully penetrate the markets and avoid being ‘locked-out’, careful identification and understanding of such constraints is essential. A recent study conducted by the OECD (1998) on measures to support the penetration of new renewable energy sources and technologies in the electricity sector distinguishes between four types of impediments[49]. Firstly, *technical impediments* that usually prevail during the initial stages of development. Secondly, *market impediments* such as inconsistent pricing regimes, difficulties in obtaining competitive forms of finance or high levels of perceived (business) risk. Thirdly, *institutional* or *political impediments* that pertain to lack of legislation and/or procedures, norms and rules for enforcement. And finally, *social* and *environmental impediments* related to a lack of awareness or experience from planners that may effectively hinder the political acceptance. In order to tackle this range of impediments, the OECD report stresses the importance of including a broad range of instruments and measures in abatement policies.

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[49] See Christiansen (2000b) for a similar analysis of factors that have constrained technological innovation in the Norwegian offshore petroleum sector.

Based upon such insights it is unlikely that one in the general case can subvert complexity *ex-ante* in terms of identifying *the* most effective or optimal (combination of) policy instrument(s) as a common panacea, without also taking into account the socio-technical and politico-institutional context in which technological innovation takes place. One should rather aim for a comprehensive policy framework or a ‘chain of support’ that includes a broad set of innovation-friendly policies and measures that does justice to the individual stages in technological change.

In conclusion, this chapter has presented an analytical framework (template) that blends a mechanistic representation of causal variable-impact relationships with knowledge and insights obtained from empirical research. Moreover, it enables the combination of qualitative and quantitative assessments. Exploiting this ‘duality’ allows the researcher to preserve the detailed knowledge of the subtleties of single cases that could be invisible in quantitative variable-oriented analysis, while also allowing for the identification of more general patterns as the number of cases analysed grows. In terms of analysing the dynamic efficiency gains of different combinations of policy instruments, one may in some cases find that other factors than policy intervention have been key determinants for success or failure. On the other hand, by comparing variations and/or similarities for a larger number of cases one may be able to identify certain general patterns, i.e., combinations of policy instruments that appear suited to promote technological innovation.

The next chapter provides an illustration of how the analytical framework can be used, by means of assessing the impact of public on the development and adoption of new renewable energy (NRE) technologies in. The key empirical research question is thus if public policy has been capable of supporting or inducing development, adoption and dissemination of NRE technologies?

6 An empirical illustration: The role of public policy in new renewable energy developments in Norway 1978-1999[50]

In spite of more than twenty years of public policies, it is fair to conclude that new renewable energy technologies have failed to live up to early projections of market penetration and public expectations (Christiansen, 2000a). Comparing the current market shares of wave, wind, solar and bioenergy with the optimistic predictions offered in the early 1980s reveals a rather depressing picture[51]. By the yearend 1999, Norway's operating wind capacity was 13 MW with annual production of about 38 GWh, or some 0.03 % of total power production (OED, 2000). There is currently no grid-connected wave power plant in Norway, and opportunities for commercial applications seem limited to specific purposes. Utilisation of bioenergy does, however, provide some 13 TWh annually, which comprise about 5% of primary energy consumption. Still, about half of this is due to conventional burning of firewood, whereas the rest is consumed mostly within the manufacturing forest industries to produce process heat and power. Somewhat unexpectedly, considering the rather unfavourable natural conditions in Norway with limited hours of daylight, small photovoltaic systems have become highly popular in certain niche markets, e.g. among owners of cottages and recreational homes. A total of approximately 80 000 units have so far been installed amounting to some 4 MW.

The pitiable market shares of NREs also reflect poor industrial development dynamics, for which there are at present only a few firms of small size within the various NRE-branches, and the rate of new entries into the population of innovators is low. At the international level, however, a combination of increasing demands, ambitious public policy goals and support programmes, improved technical performance and falling costs have over the past two decades made wind turbines and solar cells the fastest growing energy sources in the 1990s (Dunn and Flavin, 2000). How then, may one account for the rather meagre *outcome* of Norwegian efforts? Should the 'failure' to live up to public expectations be equated simply with poor technical and economic performance pertaining to NRE technologies, or are other factors such as inadequate public policies and limited opportunities for innovation to be

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[50] This chapter builds on Christiansen (2000a)

[51] See St.meld. nr 61, 1981-82 for predictions concerning the future contribution from NREs.

‘blamed’ for constraining technical change and innovation? The analytical framework outlined in chapter 5 will here be used in order to assess the role and impact of public policies, which will serve as an illustration of how the framework can be used for public policy assessments. That said, the empirical case study also serves to emphasise that policy assessments should take into account contextual features, and in particular the extent to which barriers (technological and institutional) impede the deployment and dissemination of new technologies.

6.1 Push without pull?

A key argument put forward in this report is that policymakers are unlikely to find a single-best instrument or ‘common panacea’ to facilitate and promote (environmentally benign) technological innovation. Rather, the creation of new products and markets necessitates a combination of ‘technology-push’ and ‘demand-pull’ strategies. Scrutinising the portfolio of policy instruments and measures employed to stimulate NRE developments in Norway, it is fair to conclude that policymakers have focussed almost exclusively on ‘technology-push’ strategies. Public support has mainly been restricted to funding of R&D programmes, including also some funding for market introduction and demonstration.

Considering the rather pitiable market shares of NRE-technologies and the rather limited blend of policy instruments, it seems fair to conclude that public policies have failed at creating a stable market in order to ensure *diffusion*. The limited dissemination of NRE technologies also compares well with what could be expected from the Dynamic Efficiency Matrix presented in Table 3, in the sense that none of the instruments with assumed strong impact on diffusion has been used. In comparison, economic incentives such as guaranteed minimum prices (feed in tariffs) to renewable generators have played a key role in the dissemination of for instance wind power in Denmark and Germany. Moreover, according to the push-pull argument one would ideally design an overlapping market enablement programme capable of bringing new inventions from the ‘drawing table’ to the market place. However, examining the portfolio of projects within publicly funded R&D and demonstration programmes show that there is *limited overlap* (Christiansen, 2000a).

One may thus find support for the claim that the pitiable market penetration and marginal industry developments should not necessarily be equated with a failure of existing policies and measures. Rather, one may subscribe poor development dynamics to the *absence* of measures that might have ensured viable commercial conditions for NRE technologies. Thus, whereas the stimulus of policy instruments in Norway may have succeeded in bringing certain technologies through the stages of research, development, and demonstration, other measures are required in order to develop technologies into commercial maturity.

6.2 Systemic interdependencies, network externalities and technology inter-relatedness

Another argument raised in discussions concerning the usefulness of the analytical framework was that it could be wise to select a portfolio of instruments that takes into account certain idiosyncrasies (objectives and constraints) pertaining to the specific country or sector (see section 5.4.1). This is particularly relevant with respect to various kinds of barriers that might constrain the evolution of emerging technologies (see sections 2.4 and 5.5), which seems to have strong bearings on the case of NRE developments in Norway. Hence, investigating into the technological and institutional base of the Norwegian energy sector uncovers several ways in which *systemic interdependencies* and *network externalities* impede the adoption and diffusion of NRE sources and technologies.

Firstly, infrastructures for heating are predominantly based on electricity rather than hot water[52]. The lack of water-carried heating systems effectively locks out many NRE sources and technologies that are best suited to produce heat rather than electricity; i.e. solar heating systems and certain bioenergy options. Secondly, infrastructures for production, transmission and distribution of electricity are mainly constructed on the basis of centralised power systems, reflecting the dominant position of hydroelectric power plants. A core feature of utilising NRE sources is, however, that they are commonly available locally or on site, and many NRE technologies comprise small and modular units that are fit for distributed energy

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[52] Whereas some 22% of heating systems installed in residential buildings in 1958 were based on hot water, this share had dropped to 1% in 1995 (NOU: 1998). Compared to other Scandinavian countries, the share of district heating used for heating purposes is also very low. District heating in fact covers some 50% of total space heating demand in Finland and Denmark (Christiansen and Tangen, 1999; Koefoed, 1999).

production (DEP). Potential benefits from DEP are not only enhanced utilisation of local resources and local employment, but also reduced energy losses and avoided costs associated with upgrading or expanding infrastructures for transmission and distribution. In order to stimulate DEP based on NRE it is thus pivotal that all costs and benefits associated with production, transmission and distribution of electricity are reflected in energy prices.

Another prominent feature pertaining to the Norwegian energy system that may impede NRE developments is institutionalisation and path dependency. Midttun (1988) has provided a comprehensive account of the ways in which the close ties between the hydropower and energy-intensive industries allowed expansive hydropower construction programmes to continue beyond sectoral-external economic demands. The author points to the importance of an efficient institutional basis in creating an ‘institutional lag’ or *inertia*, so that external demand for change is “delayed because of norms, decision-patterns and interest linked to a traditional sector development” (*ibid*.: 122). The ‘need’ to provide ample and *cheap electricity* supplies to uphold activities within the energy-intensive industries may thus be recognised as comprising of economic as well as institutional impediments that act as obstacles to the adaptation and deployment of NRE sources and technologies.

When analysing the impacts of institutional inertia and network externalities one should also include the central role of the petroleum sector. One may thus argue that the emergence of new sectoral interests, such as NRE, is affected through the selective institutional support that has been built up around petroleum activities. The struggle over public interest and resources should be assessed in light of the fact that oil and gas matters clearly prevail in terms of the number of sections as well as employees within the Ministry of Petroleum and Energy and other government agencies. Financial constraints also come into play, in terms that petroleum operations account for a substantial proportion of overall investments in Norway, both public and private. Accrued investments for 1998 amounted to some 80 billion NOK (OED, 1999), whereas governmental funds for NRE comprised of about 100 million. The ability to overcome vested interests and institutional inertia will most likely be decisive for the future role of NRE.

The ability to overcome vested interests and institutional inertia will most likely be decisive for the evolution of NRE. This hinges on the development of institutional capacity as well as technological capabilities, for which public policies still have a role to play. At the national level one may note that the Ministry of Petroleum and Energy recently proposed to establish a new governmental agency with the overall responsibility for renewable energy and energy conservation[53]. The new agency to be established by summer 2001 and operative from 2002 is planned as a sub-division of the Ministry[54]. Such an agency may at least in principle strengthen the institutional capacity of the renewable energy sector.

6.3 Technological opportunities and cumulativeness conditions

Recognising that technical change and innovation are first and foremost selective, incremental and cumulative processes, it is crucial to maintain an environment for trying out and testing new technologies. It is also important that users and suppliers interact in improving technological design and performance in order to harness learning effects. Such interactions are time-consuming, and should not be 'short-stopped' by top-down decisions. However, as shown in the level of public funding for NRE has oscillated throughout the period 1978-98, in terms of levels as well as the distribution between the various NRE sources and technologies.

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[53] *Reuters World Environment News*, February 25 2000, http://www.planetark.org, [25.02.2000].

[54] *Reuters World Environment News*, June 30 2000, http://www.planetark.org, [08.07.2000].

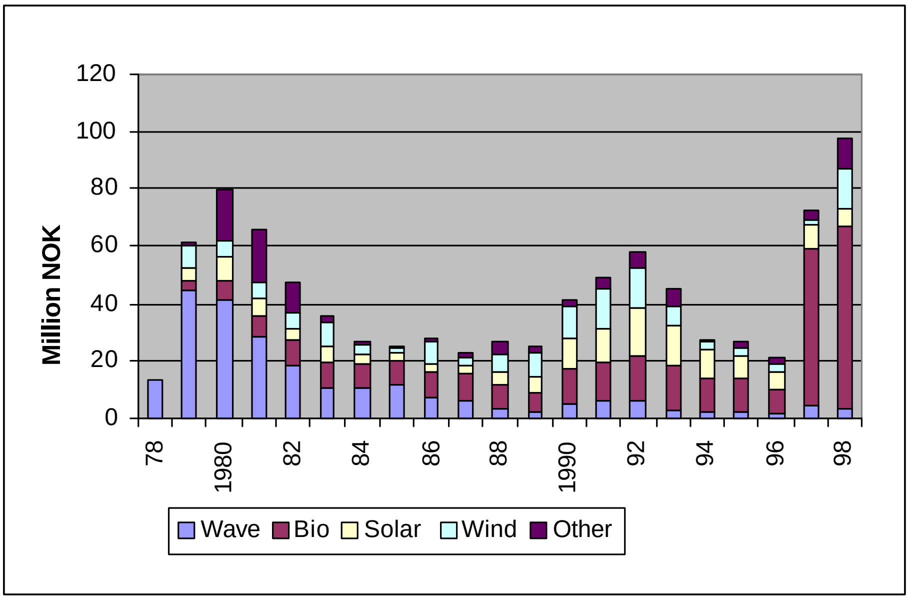

Figure 4: Government funds for new renewable energy sources from 1978-98, including support for research and development (R&D) and market introduction. Prices are in 1998 NOK corrected for inflation through the consumer price index. (*Source*: KanEnergi AS).

This oscillating pattern in Norway's public priorities has most likely impaired the conditions for accumulation of experience and maintenance of human 'know-how', both of which are perceived as detrimental to the processes of technological learning, knowledge generation and dissemination. The importance of creating an interactive environment for learning is relevant not only to provide the leverage for R&D to 'deliver the goods', but also for developments at the *firm* and *institutional/organisational level*. The 'staying power' of public policies should be recognised as an important component in the industries' perception of commercial risks, in that an unstable policy climate is likely to cause concern within industries over long-term *technological opportunities*.

Figure 4 shows that preferences have varied considerably over time, in terms that the lion's share of R&D budgets were spent on wave power during the late 1970s and early 1980s, whereas bioenergy has taken over in recent years. Lack of long-term stability with respect to both program structure and funding combines to a rather unfavourable climate for co-operation and interaction among potential investors, technology suppliers, industrial partners and other institutions. Moreover, examining the way in which publicly funded R&D programs have been organised and operated in Norway reveals that programs have been set up mostly for periods of up to four years, within which institutional restructuring and shifts in public priorities have been frequent. Considering also the relatively small number of research institutions and laboratories within the Norwegian energy system, it is in principle difficult to attract interest for participation in research areas that continuously face the risk of loosing their funding at the next crossroad. Just as weak demand side policies were identified as a market barrier to the emergence and diffusion of NRE technologies, the underdeveloped organisational and political power of the NRE industries points to institutional barriers.

Shifts in public priorities and preferences may also create uncertainty among potential investor-innovators, in terms of introducing a risk that the technology developed will ultimately not be demanded or too costly. Such shifts affect *technological* as well as *commercial expectations*. The former is an important determinant for innovators' and entrepreneurs' decisions regarding the adoption of innovations and the timing of future improvements, whereas the latter appreciates that innovators must have confidence that they are going to enjoy the rewards accruing to successful innovations. A case in point illustrating lack of confidence in the commercial potential of certain NRE technologies is Statoil's decision to pull out of a wind power project in mid-Norway, citing "unsatisfactory prospects for profitability" as the main reason[55]. In spite of increased subsidies introduced as part of a government plan to encourage investments in wind power, Statoil said it would instead turn its focus in NRE toward bioenergy for heating purposes and development of energy-efficient options such as heat pumps[56]. Another case resembling the perception of larger companies with respect to NRE was Kværner's decision to shelve its wave energy activity following the damages to one of its prototypes caused by a storm in the late 1980s and an internal reorganisation in 1990.

6.4 Lessons learned from the Norwegian experience

The empirical evidence reveals a rather depressing picture of technological and industrial development dynamics within the Norwegian NRE-sector, which also correlates with a relatively poor score using the template presented in Table 3. The only instruments that have been employed are publicly funded R&D programmes, information & education, and

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[55] *Reuters World Environment News*, January 31 2000, http://www.planetark.org, [31.01.2000].

[56] Ibid.

demonstration programmes. More recently, economic incentives in the form of tax breaks have also been introduced. As indicated by the set-scores in Table 3, these instruments offer only feeble support for technology *diffusion*, which is taken as a key explanation for the 'misery'.

Even though the outcome of public policies aimed at promoting NRE developments in Norway is pitiable, there are indeed important lessons to be learned from the perspective of linking public policies and innovation.

First, the Norwegian experience substantiates claims that a combination of 'demand-pull' and 'supply-push' measures that does justice to all the distinct phases of technological change will be required in order to create a stable and functioning market for NRE technologies. Even though there is no 'common panacea' to facilitate and promote technological progress, using the template in Table 3 suggests that, *inter alia*, economies of scale could provide the leverage for NRE sources and technologies to become commercially viable. Greater demand for NRE *sources*, leading to greater demand for NRE *technologies,* may thus be required to spur mass production of passive/active systems to utilise solar energy, refined bio-fuels, or systems utilising energy from the waves. Moreover, in order to complement 'technology-push' with 'demand-pull' strategies, at least two approaches seem appropriate for Norwegian circumstances. One path involves designing policies in order to stimulate a market for technology suppliers, which mimics Germany's policy of *mandating* bilateral contracts at fixed prices between NRE generators and grid operators (direct regulation). Another route is that of establishing a guaranteed market for sales and trade of green power, in terms that suppliers are obliged to include a fixed volume of green power in their supply portfolios using renewable portfolio standards or green certificate trading. Within both approaches it may prove beneficial to pay attention to aspects such as network and capacity building and the role of third-party actors (consultants and supply industries) in the design of policy measures.

Second, owing to the long lead-times required for new technologies to traverse from the stage of invention to marketable innovation and diffusion, it is also critical that policymakers maintain a long-term perspective with respect to public policies. Third, it may be useful for the government to use its buying power to improve market opportunities for technology suppliers. And finally, the Norwegian case underpins the importance of removing or overcoming barriers that constrain the development and deployment of new (NRE) technologies. Carefully designed public policies and enlightened government intervention may avoid unwanted path dependence by guiding technological developments in a direction beneficial to society and the environment.

7 Concluding remarks

The key objective of this report has been to develop an analytical framework for analysing and assessing how, and the extent to which public polices may provide continuous incentives for environmentally benign technological innovation; i.e. achieve dynamic efficiency gains. This objective was partly motivated by the increasing recognition that the development, adoption and diffusion of cleaner energy technologies are likely to be key determinants to success or failure in environmental and climate policy, at least in the long term. Hence it is crucial that policymakers have capacious knowledge of factors that promote, or hinder technological change, and the role of public policy in such processes.

In order to provide a coherent framework for dynamic efficiency assessments, the report combines insights from analytical and empirical research on the issues of technological change and policy instrument choice. Even though our understanding of the interplay between technological change and public policy is still somewhat elusive, two key observations were made. Firstly, that the processes of technological change and innovation can be portrayed as a set of distinct and interrelated stages, each encompassing a set of driving forces and mechanisms. Secondly, that there is no single instrument or 'common panacea' that seems capable of facilitating the entire process of technological from invention to diffusion. In sum, these observations suggest that an innovation oriented policy strategy should include a carefully selected portfolio of instruments that does justice to all stages in the technology development cycle. On this basis, the report presents an analytical framework based on fuzzy set analysis to serve as a focusing device for dynamic efficiency assessments and empirical research.

The framework blends a mechanistic representation of causal variable-impact relationships with knowledge and insights obtained from empirical research. Moreover, it enables the combination of qualitative and quantitative assessments. Exploiting this 'duality' allows the researcher to preserve the detailed knowledge of the subtleties of single cases while also allowing for the identification of more general patterns as the number of cases analysed grows. The usefulness of the template is illustrated in terms of two stylised examples, followed by discussions on the scope and limitations in making use of the framework.

Finally, the report includes an empirical case for illustrative purposes, analysing the development of new renewable energy technologies the Norway. The case study substantiates claims that a broad range of policy instruments are needed to ensure viable commercial conditions for NRE technologies, inter alia combining technology-push with demand pull strategies. Moreover, the case highlights that oscillating public priorities, systemic interdependencies and institutional inertia may hamper the processes of technological change and innovation.

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