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Energy Policy 33 (2005) 1557–1576

ENERGY POLICY

www.elsevier.com/locate/enpol

Near-term technology policies for long-term climate targets—economy wide versus technology specific approaches

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Abstract

The aim of this paper is to offer suggestions when it comes to near-term technology policies for long-term climate targets based on some insights into the nature of technical change. We make a distinction between economy wide and technology specific policy instruments and put forward two key hypotheses: (i) Near-term carbon targets such as the Kyoto protocol can be met by economy wide price instruments (carbon taxes, or a cap-and-trade system) changing the technologies we pick from the shelf (higher energy efficiency in cars, buildings and industry, wind, biomass for heat and electricity, natural gas instead of coal, solar thermal, etc.). (ii) Technology specific policies are needed to bring new technologies to the shelf. Without these new technologies, stricter emission reduction targets may be considered impossible to meet by the government, industry and the general public, and therefore not adopted. The policies required to bring these more advanced technologies to the shelf are more complex and include increased public research and development, demonstration, niche market creation, support for networks within the new industries, standard settings and infrastructure policies (e.g., when it comes to hydrogen distribution). There is a risk that the society in its quest for cost-efficiency in meeting near-term emissions targets, becomes blindfolded when it comes to the more difficult, but equally important issue of bringing more advanced technologies to the shelf. The paper presents mechanisms that cause technology look in, how these very mechanisms can be used to get out of the current "carbon lock-in" and the risk with premature lock-ins into new technologies that do not deliver what they currently promise. We then review certain climate policy proposals with regards to their expected technology impact, and finally we present a let-a-hundred-flowers-bloom strategy for the next couple of decades.

Keywords: Climate change; Innovation; Technology policy

1. Introduction

The goal of the UNFCCC (1992) is "stabilisation" of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The UNFCCC does not attempt to define the concept of dangerous interference with the climate system. Precise statements of what is "dangerous" are not possible, since (a) the degree of harm from any level of climate change is subject to a variety of uncertainties and (b) the extent to which any level of risk is "acceptable" or "dangerous" is a value judgment (Azar and Rodhe, 1997; Azar and Schneider, 2001).

The only reasonable way to deal with this uncertainty is to act now so as to preserve options—including that of stabilising at low-concentration targets, i.e., at least below 450 ppm since that may be necessary if we are to avoid very serious climatic changes (see Azar and Rodhe, 1997; Azar and Schneider, 2001; O'Neill and Oppenheimer, 2002).

Thus, early action is needed along at least four dimensions:

- Take measures to achieve actual emission reductions in the near term. This is important for two reasons: (i) unabated emissions in the near term will make it technically and politically more difficult to meet stringent targets, below 450 ppm, in the long term (see Grubb, 1997; Azar, 1998; O'Neill and Oppenheimer, 2002), and (ii) by implementing abatement policies, e.g., policies that increase CO_2 emission prices, policy makers (and other actors) will learn how the energy system responds and this will make it possible to adopt better policies.

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0301-4215/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2004.01.012

- Develop international institutions and rules of games that are needed to address this global problem (Nordhaus, 2001).
- Develop new technologies that are required to meet future more stringent abatement targets.
- Strengthen private-sector and non-governmental organisations (NGOs), and networks of actors that recognise the need for stringent climate policies.

The Kyoto protocol is an important first step to address these issues. Kyoto addresses near-term reductions (our first bullet) and the development of institutions (the second bullet), and in doing so, also some technology development (bullet three) and actor support (bullet four) will be stimulated. Reducing the emissions of CO_2 through a cap-and-trade system will create incentives to develop new technologies, and will build a stronger lobby for climate policies as more companies recognise the benefits of aggressive climate policies.

The Kyoto protocol should be understood as a first step towards more stringent targets. Stabilising atmospheric concentrations between 400 and 550 ppm, requires global per capita emissions to drop to 0.2–0.7 ton C/cap/yr by the end of the century. This can be compared to the current (1999) emissions of 5.5 ton C/cap/yr in USA, 2.5 ton C/cap/yr in Japan, 2.0 ton C/cap/yr in Western Europe and 0.6 in China and 0.3 in India and Africa on average (see Marland et al., 2001). Thus, emissions in the industrialised countries may have to drop by a factor of 10 or more on a per capita basis over the next 100 years, and there is not a large space for increased emissions in many developing countries in the long term. Rather, a radical transformation of the energy system is required.

From this perspective, the Kyoto protocol should primarily be judged on the extent to which it puts industrialised countries in a better position to take on and meet the much larger emission reductions that are necessary in subsequent commitment periods.

However, meeting the Kyoto target, based on current least-cost criteria, would mean extensive purchases of hot air from Russia and sinks in developing and developed countries, substitution of natural gas for coal in Europe and the US and perhaps some diffusion of biomass and wind energy, resulting in only weak incentives to develop new technologies, and actors that promote the new technologies, which would support more stringent policies, would remain weak. If technology specific policies are not enhanced in parallel with the Kyoto protocol, there is a risk that the world will not have enough advanced technologies developed so that more ambitious objectives for post-Kyoto periods are not judged credible.[1] Thus, if cost-efficiency in meeting the Kyoto targets is the overriding goal, then our actions might be sub-optimal when it comes to positioning us to meet the ultimate objective of the climate convention.

Meeting near-term emission targets at a low cost is clearly a very important political objective. The higher the immediate cost of meeting any target, the higher the resistance will be to adopting more stringent subsequent targets. Our point in this paper is that we should not *only* look at near-term cost-efficiency, because we might then become blindfolded when it comes to the more difficult, but equally important longer-term issues that we have to face now. It is critical that near-term climate policies recognise all four objectives: near-term abatement, institution building, technology development and the strengthening of proactive actors.

The aim of this paper is to review the impact of some current climate policy proposals when it comes to technology development based on some insights into the nature of technical change, and to offer policy suggestions on what needs to be done when it comes to develop more advanced carbon efficient technologies.

In Section 2, some insights into the nature of technical change, and in particular technology lock-in and path dependency, are described. In Section 3, we move on to describe the types of policy measures that are required. In Section 4, we look at some current technology policy proposals. In Section 5, we offer a tentative list of what at least needs to be done when it comes to technology policies over the next 10 years. Some final conclusions are offered in Section 6.

2. Path-dependent technical change

As indicated above, a stabilisation of the carbon dioxide concentration at a level that prevents dangerous anthropogenic interference with the climate system would require an almost complete dismantling of existing energy systems and a tremendous growth of several new technological systems.

Such a technological transformation is complicated and it is not just a matter of replacing one technology with another from the shelf. Technical change encompasses at least three steps: *Inventions* as new ways of doing old or new activities, *innovations* which are often seen as a modification of a creation/invention to make it suitable for adoption, and finally, *diffusion* as the process of disseminating inventions and innovations. Taking an invention from the laboratory to a viable commercial product is normally a long, uncertain and

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[1] This issue is never appropriately addressed in modelling studies of the cost of meeting the Kyoto protocol, and subsequent targets. In such studies, the targets are set exogenously and therefore the sole purpose is to find the least-cost path towards that target, but no attention is paid to the equally, or perhaps more important question of how to set and negotiate targets.

Table 1
Mechanisms leading to lower production costs with increased adoption

Economies of scale in production:	Production costs per unit of output decrease when fixed costs are spread over an increasing production volume. Increased production volumes also enable increased division of labour (Smith, 1776).
Learning by doing:	Production processes and organisation are refined and the skill of workers increases with cumulative production (Wright, 1936; Hirsch, 1956; Arrow, 1962).
Incremental product development:	Learning by doing and learning by using can feed back into incremental product development. The product is refined to increase the performance-to-cost ratio and better meet the needs of users and producers.
Economies of scope—complementary resources and production processes:	The growth of one technology may induce a use of byproducts. The value of the byproduct can lower the net cost to produce the initial main product. The multiple outputs of oil refineries may serve as example.

Table 2
Mechanisms making a technology more attractive for users and investors with increased adoption (regardless of price)

Decreasing uncertainty:	The adoption of a technology will decrease the uncertainty of its merits (Arthur, 1988; Cowan, 1991). Risk adverse producers, users and investors prefer a better-known technology. This is probably of extra importance when it comes to consumer goods, such as private cars and domestic heating systems.
Learning by using:	The performance of a technology increases and service costs decrease when users gain experience, in particular valid for complex capital goods such as aircraft and power plants (Rosenberg, 1982), but also maintenance of consumer capital goods such as cars and houses. As an example, the output from 1 MW of installed wind power capacity has increased over the last decade due to increased operating experience.
Economies of scale in consumption—user networks:	The benefit that a consumer derives from using a good sometimes depends on the number of other consumers purchasing compatible items (Katz and Shapiro, 1986). For example, if many use the same standard (e.g., VHS videocassette recorders, direct current PV systems and private cars), the cost of complementary goods (pre-recorded cassettes, low voltage appliances and roads), will decrease and their availability will increase. The availability of machine service and spare parts will also increase.

painful process of bringing different competencies together. A new technology must first get through the process of getting to the shelf before it can be pulled from the shelf.

In addition, the direction of future technology development is not completely flexible but is constrained by historical trajectories. Technical change is sticky and path-dependent (David, 1985). The fundamental mechanisms behind path-dependency are positive feedbacks or increasing returns to adoption (Arthur, 1994). The cost and performance of a new technology are more uncertain and often inferior to the cost and performance of entrenched technologies. When a technology is adopted, a number of positive feedback mechanisms will decrease its production costs (Table 1). Increased adoption will also create additional benefits for users that decrease their hesitation to invest (Table 2).

Path-dependency implies that entrenched technologies have a distinct advantage over newcomers, not because they are inherently better, but because they are widely used. In this sense, positive feedbacks lead to technology lock-in (Arthur, 1988).

In some cases it is not just a matter of a cost advantage and decreased uncertainty. When the technical, institutional and behavioural environment is shaped through additional feedback mechanisms (Table 3), Hughes (1983) talks about *technological systems* that gain *momentum* as they grow. Unruh (2000) use the term *techno-institutional complex* for the most pervasive form of technological systems that through the co-evolution of technologies and institutions penetrate the economy at the macro-level.[2]

Over the last 200 years fossil fuels has formed a techno-institutional complex and created a carbon lock-in (Unruh, 2000). Escaping carbon lock-in will be a slow process extending over many decades, as was the growth of the fossil fuel system. For example, it took a century for oil to grow from its market share of 1% of world primary energy supply in the 1870s to the peak at 46% in 1973 (Fig. 1).[3]

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[2] Similarly, Grübler (1998) and Freeman and Perez (1988) use the terms *technology cluster* and *techno-economic paradigm*, respectively, for groups of technologies that dominate certain historic periods to the extent that they change the way the whole economy works.

[3] It has been shown that large-scale technological shifts take several decades—for primary energy and some infrastructures perhaps even a century, time-spans significantly longer than the technical lifetime of the capital stock itself (Grübler, 1997). Also the time between invention and innovation, may span over many decades (Rosegger, 1996). For instance, half a century elapsed between the discovery of electromagnetic induction (by Faraday in 1831) and the development of the electric generator (see Sharlin, 1961), although it can be noted that the time lag between invention and innovation has shortened over

Table 3
The position of an established technology is further re-enforced by moulding the surrounding technical, institutional and behavioural environment through additional lock-in mechanisms

Technological inter-relatedness:	As a technology becomes entrenched it becomes interrelated to other technologies along the production chain (Frankel, 1955). A dominant technology becomes dependent on industries supplying design-specific inputs. As the dominant technology grows these industries can benefit from learning and scale economics. Downstream, it limits the possible set of technologies that consumers will use. New technologies need to be *compatible* with the old set otherwise the whole set need to be changed. Hydrogen cars are useless if there are no hydrogen filling stations.
Vested interests:	Firms have fixed costs in capital stocks that need to be recovered (Grubb, 1997), and they have invested in a knowledge base that they want to exploit (Nelson and Winter, 1982; Dosi, 1988). Groups of users have invested in learning and designed their lives in relation to a technology. For example, how we choose to locate our homes is highly dependent on technical means of transportation and how we design our days are dependent on available technical means of storing and cooking food. Labour unions represent workers that have invested in education and located their living in relation to work places. Academics have made a career based on a specific knowledge base.
Bounded rationality:	Decreasing technological variety, or *technology closure* and the *stabilisation* of an artefact, imply that what engineers and other social groups think the artefact, e.g. an automobile or a power plant, should look like is narrowed (Dosi, 1982; Bijker, 1995). The evolved consensus of the main purpose of the technology, how it should be designed, what kind of materials it could be made of, what problems there remains to be solved, how the technology should be assessed, etc., limit the vision of business leaders and the imagination of engineers and consumers.
Directed education and research:	To enhance technological progress in an area, public funds are used for specialised education that provides skilled labour and new academic disciplines that provide knowledge (e.g. AC engineering, Hughes, 1983; and highway and automobile engineering, Unruh, 2000).
Legal frameworks:	Legal frameworks that are designed to fit the use of an incumbent technology may effectively lock out new technologies. As a new technology grows, the institutional framework needs to be adapted. If groups that advocate a technology, because of vested interests and bounded rationality have enough power (Bijker, 1995), they may not only re-enforce the trajectory of the technology by investing in it themselves but they may also bound the rationality of other groups in the same direction and affect how public funds are used and legal frameworks are designed.

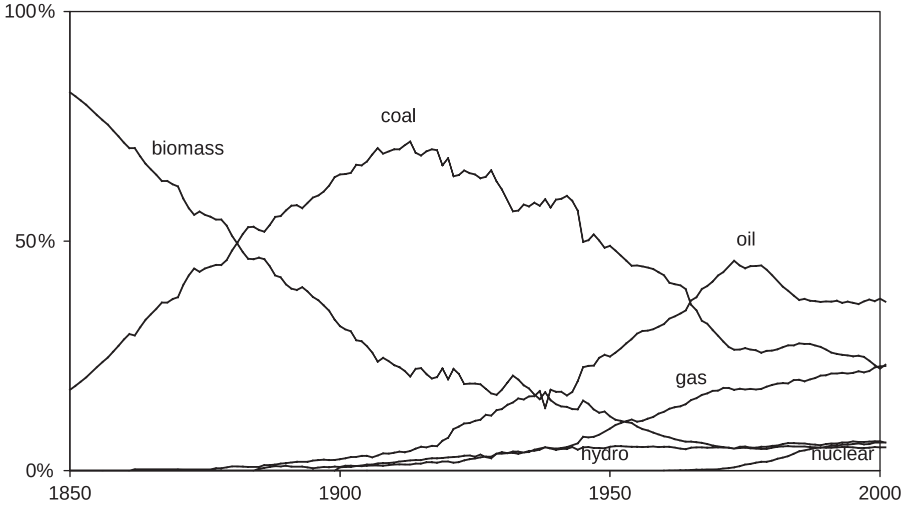

Fig. 1. Shares of world primary energy supply 1850–2000. *Sources*: Data for 1850–1995 from Grübler (1998) and 1995–2000 from BP (2002).

The pervasiveness of the fossil fuel system is not only a result of historical coincidences, but also a result of inherent physical and chemical properties of fossil fuels that tend to make them more attractive from a variety of perspectives (costs, transportability, etc.).[4] Thus, it is unlikely that "spontaneous" technical change will take us out of the carbon lock-in. And the fact that we are so locked into carbon implies that there will be large initial opposition to change and policies to promote change. There are many stakeholders, not to say all of us, that have vested interests in the prevailing system. Habits,

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(*footnote continued*)
time following the introduction of scientific labs in industrial companies (Rosenberg and Birdzell, 1986). Further, the time between innovation and when a 1% market share is reached can also be considerable in large systems like the energy system.

[4] Even though one should be aware of that also our perception of what constitutes attractive properties has been formed by the system.

institutions and technological networks are adapted to the use of fossil fuels. Change is difficult and the drawbacks for individuals of implementing, e.g. carbon taxes, are obvious while the negative feedback on actions is diffuse and distant in space and time. Hence, political courage will be necessary to induce change.

How can this political courage come about? Unruh (2002) suggests that policy that promotes institutional change is unlikely to forego social change and that social change might require focusing events like major climate related catastrophes. Unfortunately, this could very well be true, but we also see other options. Scientific evidence of climatic change, a gradual adjustment of carbon prices and the creation of technological alternatives and actor groups that support them and benefit from them could turn the balance in favour of more proactive policies. We consider the Kyoto protocol and the rapid growth of some renewable energy technologies supported by technology policies in some countries as positive signs. But there is also a risk that initial steps might lead to dead ends. In the following section, we review a number of policy instruments and how effective they might be in bringing about the necessary changes.

3. Policy instruments to achieve low CO_2 emissions trajectories

The time frames involved in developing new technological systems seem to be of the same magnitude as the time frame of CO_2 reduction, roughly a century. Consequently, there is a need now to start implementing policies to set society on a trajectory towards low emissions. Two related questions emerge: (i) what policies are effective and (ii) what is required to gain enough support for different policies. This section will focus on the first question and we consider economy wide price adjusting instruments and technology-fostering instruments, but we also note that a strategically planned introduction of these instruments may increase the number of actors that support carbon abatement policies and therefore may make it easier to introduce even stronger policies in the future (thereby also addressing the section question).

3.1. Adjusting prices

Economy wide price-based incentives are by many viewed as the most cost-effective way to reduce CO_2 emissions (see Sterner, 2003, for a detailed review and assessment of environmental policy instruments).

A price on carbon dioxide emissions implemented via a tax, or a cap-and-trade system, operates in three ways: it increases the competitiveness of carbon neutral technologies, it raises the price of energy and therefore induces energy efficiency improvements and savings, and it offers incentives to private actors to develop more advanced supply, conversion and end-use technologies (e.g., a large utility will divert more research into say wind energy if they foresee that the cost of carbon emissions will increase over time).

Although the experience with carbon taxes is limited, there is empirical evidence suggesting its effectiveness. In Norway in 1996, a carbon tax set at 59 USD/ton CO_2 on off shore operations gave Statoil incentives to sequester the CO_2 emissions from its natural gas extraction.[5] In this case, it became economically profitable to sequester the CO_2 and store it in an aquifer 1000 m below sea level (Herzog et al., 2000).

The Swedish heating sector may serve as a second example. Following the oil crises in the 70s, there was an ambition in Sweden to become less dependent on oil. In the 80s, the tax on oil was increased and it led to an expansion of biomass, coal, electric boilers and heat pumps in district heating (Fig. 2). There were also tax increases on the use of coal, but on a kWh basis the tax was lower than the tax on oil. Coal was seen as a promising alternative to oil. However, in the 90s attention shifted towards CO_2. In 1991, a tax based on the carbon content of the fuel largely replaced the energy taxes on the different fuels, so that the total tax on oil increased by 30% and coal with 90% (Sven Werner, pers. comm., December 12, 2002; Swedish Energy Agency, 2002). This led to an accelerated use of biomass, and the share of fossil fuels declined from 91% in 1980 to 35% in 1990 to 16% in the year 2000. (The Swedish carbon tax, about 400 USD/ton C, is levied on the transportation sector, residential heating, and at a reduced rate on industrial CO_2 emissions, but the electricity sector has been exempted.)

A tax rate of 70 USD/ton C (which might be required to meet Kyoto, although uncertainty ranges are wide[6]) would raise the price of electricity from coal (assuming a conversion efficiency of 40%) by 15 USD/MWh electricity, which would make wind, biomass, natural gas and possibly light water reactors (LWRs) competitive. The cost of heat and process heat from oil and coal would increase above the present price by 1.6–1.9 USD/GJ, respectively, which would make biomass competitive in many applications (the price of biomass at

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[5] Natural gas contains CO_2, in this case 9%, that has to be removed from the gas before it is sold. Normally, it is just vented into the atmosphere.

[6] IPCC (2001, p. 537) and Persson and Azar (2002). The estimate assumes that the US participates. In the absence of US participation, there is a risk that the cost drops to zero because of the large surplus of hot air in the former Soviet Union (FSU), at least under assumption that the Kyoto–Marrakech system will operate like an entirely free market (see Nordhaus, 2001). This is however, rather unlikely, for several reasons. FSU may act as a "monopolist" and thereby increase the permit price (see Persson and Azar, 2003), and EU/Canada/Japan is unlikely to pay Russia for doing nothing.

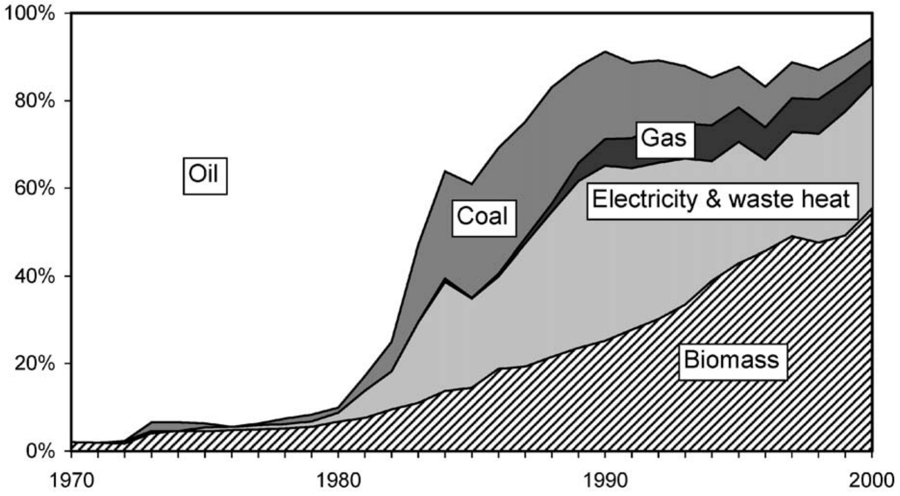

Fig. 2. Fuel use shares in Swedish district heating. The impact of a carbon tax, introduced in 1990, led to acceleration in the use of biomass. *Source*: Swedish Energy Agency (2002).

present in Sweden is 2.7 USD/GJ and the price of low-cost coal in the US is around 1 USD/GJ).

It should also be noted that economy wide instruments not only affect price relations but also represent a signal of political ambition that affects expectations about the future and thereby the direction of search for new solutions in industry.

3.2. Fostering immature technologies: technology policies for the development of more advanced technologies

Economy (or sector) wide price instruments are effective to pick close to commercial technologies from the shelf. However, in spite of the implementation of gasoline taxes in some countries and carbon taxes in Scandinavia, the last decade of debate has shown that implementing such incentives at a global level is going to be politically very difficult. The absence of mature carbon neutral technologies means the absence of strong industrial actors in favour of a carbon tax. The political influences of the actor groups that are likely to benefit from a tax are much weaker than those that have a lot to lose. This could explain why it has been politically feasible to implement a high carbon tax (on transports and heating but not the energy-intensive sector) in Sweden, a country with a large forest industry and no fossil fuel resources. Similarly, it seems clear that the absence of strong national oil producers is one of the reasons why petrol taxation has been more feasible in Europe than in the US. Hence, policies that more directly stimulate growth of carbon neutral technologies could be a prerequisite for the implementation of ambitious economy wide price instruments (institutional feedback loops is further discussed in Section 3.3).

In addition, the tax levels or permit prices required to meet near-term targets are not likely to be large enough to spur technological development of more advanced technologies.

The tax rates required to meet Kyoto are unlikely to provide sufficiently strong incentives:

- to start the development of more advanced energy technologies, e.g., solar hydrogen options and fuel cells, that are required to meet more stringent climate targets;
- to prepare for the emergence of related new infrastructure, e.g., hydrogen distribution systems, and
- to decrease energy use that results from decisions for which the cost of energy is of minor importance.

The above-mentioned tax of 70 USD/ton C would, e.g., increase the price of gasoline at the pump by only 0.04 USD/l, which would be far from enough to, by itself, stimulate a transition to hydrogen or, for that matter, liquid hydrocarbons based on biomass (Azar et al., 2003). Ethanol from tropical sugar cane is a potential exemption. To make solar photovoltaics (PV) competitive on most grid-connected markets the carbon price would need to exceed 1000 USD/ton C.[7] Examples of the third category are the reluctance to make no-regrets energy efficiency investments in some industries, in particular construction (Ayres, 1994; Sorrell, 2003) and our indifference to energy cost when we, e.g., select among holiday trips.

For these reasons, other policies, complementary to economy wide price incentives are crucial. Our focus is on policies related to the development of more advanced technologies; we deal to a lesser extent with policies

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[7] A carbon tax of 1000 USD/ton C would increase the price of electricity from coal by about 200 USD/MWh. This is less than half of the current price of PV electricity in Germany. Japan is an exception mainly due to high electricity prices.

related to infrastructure and not at all with energy intensity issues.[8]

That radical innovations manage the transition from invention to competitiveness and diffusion without technology specific governmental support is probably more exception than rule. In fact, many products that we now consider highly commercial have a history of subsidisation. For example, various kinds of government policies supported the development of semiconductors, computers and jet aircraft to the point when commercial markets were established (Nelson, 1982). Examples from energy conversion technologies include not only nuclear power (Goldberg, 2000) but also gas turbines, the currently least expensive technology for electricity generation, that benefited from spill-over from military research and development (R&D) of jet engines since World War II and onwards (Norberg-Bohm, 2000).

A broad spectrum of policy instruments that directly support the development of specific technologies is available, such as R&D funding, demonstration, network formation, niche market management, standardisation and adaptation of the educational system.

Funding of R&D is of course crucial for technologies that are not expected to become commercial in the near term. But, as noted by Kline and Rosenberg (1986), it is not only basic scientific research that requires funding but also research that supports the whole innovation chain, including process technology, systems research and market assessments. The required magnitude of change and the long-term commitment pose a formidable task. This has made Hoffert and Caldeira (1998) to call for efforts "pursued with the urgency of the Manhattan Project or the Apollo space programme" and Freeman (1996) to ask for a revitalisation of the idea of large technology push programmes.

In light of this, the ongoing reduction in energy R&D is disappointing. Margolis and Kammen (1999) conclude that while total R&D (private and public) in the USA increased by almost a factor of two between the late 1970s and 1996, R&D investments related to energy decreased by more than a factor of two over the same time period. Public R&D on energy peaked at 7.5 billion (1995) USD in 1979 and has dropped ever since and is now down to 2.3 billion USD. The decline is mainly due to a dismantling of nuclear research (dropped from 3.4 billion USD to a tenth of that level), but also due to a drop in coal research (which dropped from 1.4 billion USD in 1980 to 100 million in 2000) and renewable research (which peaked at 1.3 billion USD in 1980 and is now down to 200 million USD).

The pattern is similar in other countries except that Japan has maintained its strong nuclear power programme that amounts to some 80% of OECD public R&D investments in fission. Total public R&D spending in energy has not dropped in Japan (see Fig. 3).

Margolis and Kammen also notice that R&D intensity of the energy sector (defined as R&D percentage of net sales) is low compared to other industries. For instance, total R&D spending lies in the range 2% and 3.5% of GDP in countries such as Denmark, Finland, France, Germany, Japan, Sweden, UK and the US (according to OECD main science and technology indicators, cited in Steil et al., 2002). And, while US industries in general invested 3.1% of annual sales revenues on R&D in 1994, US utilities, on average, invested 0.3% of their sales (Dooley and Runci, 1999). Dooley (1998) observe that the deregulation of electricity markets cause private investments in the energy sector to decrease even more and become more oriented towards investments with short payback times.

Demonstration may function both as a test that generates knowledge of system performance and user response that can be fed back into development, and as an advertisement that raises the level of awareness of the technology. In early phases when performance uncertainty is high and awareness is low, demonstrations may get widespread attention and strengthen the support for other policy instruments. The PV facade that Flachglass put up in Aachen in 1989 attracted interest from architects around the world. Together with other very visible installations that followed, it is believed to have influenced the perception of solar cells by politicians and the public in Germany and helped to lay the ground for the 100 000 roof and the 99 pfennig programmes that sparked off the German PV market a decade later (Jacobsson et al., 2004). However, when a certain level of experience has been achieved, demonstrations have played out their role (Norberg-Bohm, 2000).

The formation of networks around the new technology may need to be supported. To form a new technological system the interaction of a number of actors is crucial to disseminate knowledge and visions (Jacobsson and Johnson, 2000). For example, to make a building integrated PV market grow, communication channels between research institutions, PV manufactures, roofing companies, architects, glass manufacturers, the construction industry and electricians need to be developed. Initial networks may develop around demonstration projects (Karlström and Andersson, 2003). Government can also facilitate networking by arranging or supporting conferences, workshops and meetings, and by supporting industry newsletters and develop organisations for collaborations. For example, the US government sponsored a number of courses and conferences with participants from industry, authorities and universities that were seminal to the formation of the

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[8] Organisational, cultural and regulative changes are probably needed as complements to economic incentives to decrease energy use that results from decisions for which the cost of energy is of minor importance.

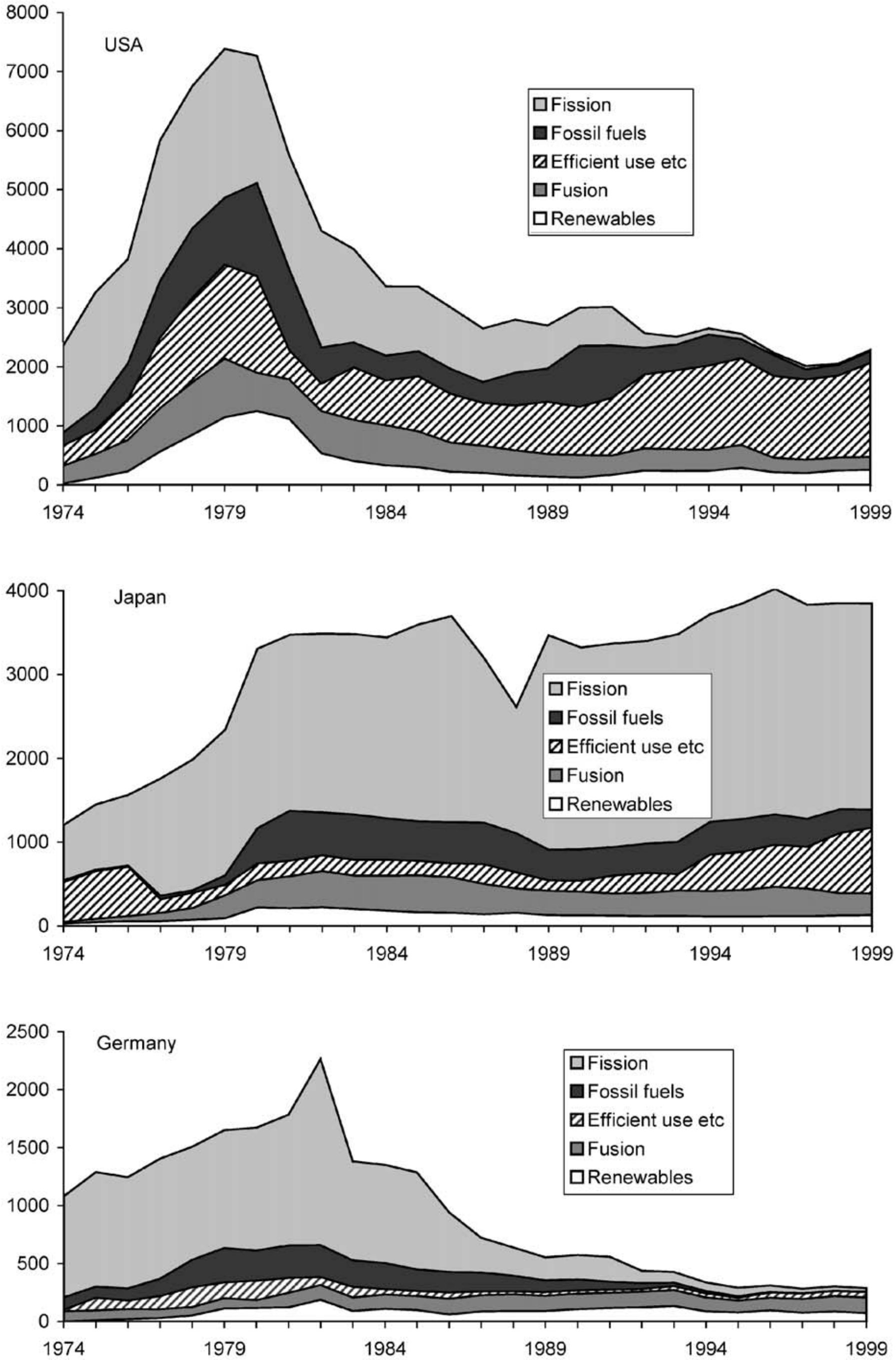

Fig. 3. Public energy RD&D funding in USA, Japan and Germany (MUSD/yr). *Source*: IEA (2001).

computer industry in 1945–1946 (Katz and Phillips, 1982). This role of government is clearly not needed when an industrial sector has become mature with a large market and billions of USD in turnover, since the sector by then would form such networking by itself. It is during the very early phase that government support is required. The formation of such new networks will thus be necessary not only to develop the technology but also to balance the political power of networks around old technologies.

Government supported *market formation* has proved to be critical when a private demand for a product has yet to be formed (as for computers in the 1940s, Katz and Phillips, 1982) or when costs need to be bought down to become competitive on commercial markets (as for new generations of semiconductors in the 1950s and 1960s, Levin, 1982). Policy may form markets in many ways and policy design will have an effect on technology choice and speed of development. The carbon tax discussed above will create a market for some technologies that are close to competitive but not for others that are not as mature. The second category needs more exclusive niche markets that tolerate higher prices. In some cases commercial niche markets are available (such as PV applications for satellites, consumer electronics and off-grid power generation). If not so, or to increase diffusion rates, there is a need for government created niche markets (Kemp, 1994; Kemp et al., 1998; Norberg-Bohm, 2000; Jacobsson et al., 2004).

The rationale for niche market creation is that increased adoption could lead to lower costs and increased utility via the positive feedback mechanisms listed in Section 2. It has been shown that costs decrease most rapidly in the early phases of the innovation and diffusion process. This observation has been formalised in so-called learning or experience curves that give the cost reduction as a function of cumulative production.[9] For each doubling of cumulative production, costs decrease by a fixed percentage. Thus, even if the unit cost for new technology tend to be high, reductions of unit costs and thus competitiveness may be gained at low total cost, since small volumes are needed to decrease the cost in the early phases of the technology's life cycle. The prospects for cost reductions with increased production (the steepness of the experience curve) appear to be higher for small-scale power plants and modular technologies than for large-scale plants (Neij, 1997). More niche markets are also available for smaller units that could tolerate higher prices.

If policy makes use of dynamic learning and scale effects, the cost of introducing small-scale technologies such as wind power and PV could be moderate in comparison to the cost of economy wide price incentives, if the subsidies are phased out over time, as the technology grows mature (see calculations in Section 5 and Sandén, 2003).[10] Table 4 lists four types of policy instruments to create niche markets.

While investments in research, development and demonstration (RD&D) tend to decrease (Fig. 3), there are now examples where this is more than compensated for by market creation policies. In Germany, e.g., the RD&D budget of PV and wind power was about 0.04 billion € in 2002 (IEA, 2004), while the compensation for electricity production from PV and wind power plants under the Renewable Energy Sources Act (EEG) exceeded 2 billion € (Jacobsson and Lauber, 2004).

Regulations may need to be adjusted so that they do not automatically discriminate against new technologies. For example, the diffusion of wind power and building integrated solar thermal panels are in some areas slowed down because of difficulties with getting building permits (Jacobsson and Bergek, 2003; Kåberger et al., 2003). To enable faster diffusion and learning and to reduce uncertainty, *standardisation* of test and permit procedures and product design is needed. Governments may take a role in such standardisation procedures.

The educational system needs to be adjusted to be able to supply new industries with a skilled workforce and new entrepreneurs, and to increase the general awareness in society (Jacobsson and Johnson, 2000). Levin (1982) suggests that the US public support for higher education in electronics in the 1950s and 1960s not only satisfied the demand from industry but also in addition created a supply push of educated people.

The development of new infrastructures and integrated systems such as hydrogen infrastructures or co-generation of heat and electricity in combination with district heating and cooling is more complex. It could slowly evolve from a changing set of individual technologies but it is likely to require additional policy intervention at the system level.

Broadly acceptable *visions or leitbilder* will be needed to guide the multitude of decisions that are to be made by different actors. Insights gained when developing an infrastructure for natural gas can be useful when planning for a hydrogen infrastructure. Kaijser (1996) reviews the political and industrial activities in Holland that preceded the exploration of the Groningen field. Since there are large investment costs involved when developing such an infrastructure, it was important that a large market for the gas was rapidly built up, that long-term contracts were signed and that a sufficiently large majority in the parliament was secured in favour of the project. The latter factor was important in order to ensure industrial actors that the rules of the game would not suddenly change in a direction unfavourable to natural gas users. This is one example of the role leitbilder can play. Of course, if too much devotion is given a certain vision, then it may be difficult to switch course if that turns out to be needed (see also Section 3.4).

Given the long time horizons of infrastructure change, visions need to be transferred to the *physical planning* of cities at an early stage, not the least to avoid structural change that blocks the introduction of new energy infrastructure.

3.3. Virtuous circles, timing and continuity

Policy instruments need to be co-ordinated to enable a balanced development of new technological systems (Jacobsson and Johnson, 2000; Norberg-Bohm, 2000).

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[9] Learning curves normally refer to labour costs alone while experience curves refer to total costs. The sources of cost reduction are then a combination of learning and scale effects, incremental product development and changes in input prices (Neij, 1997).

[10] Wind and PV power plants are not necessarily "small-scale". The point here is that individual modules are small, but wind and PV farms can be huge. While applicable to small-scale uses, they are not inherently small as is, e.g., mini- or micro-hydro.

Table 4
Four types of policy instruments for niche market creation

Government procurement:	This is the most direct option. Military spending in the USA has, e.g., been decisive for the development of semiconductors, computers, aircraft, gas turbines, nuclear power and PV (Nelson, 1982). Governments can also arrange technology procurement (Koch, 2000), that is a government agency acts as a broker that identifies a bundle of potential customers for a new technology and then arrange a competition among suppliers. This guarantees a first market.
Green labelling:	Green labelling is way to support articulation of the demands of certain customer groups, which may be organised by governmental bodies or NGOs. In the 5 years following the deregulation of the electricity market in Sweden in 1996, the market for environmentally labelled electricity grew to 9 TWh/yr in 2000 (Kåberger, 2003), but this growth consisted primarily of a relabelling of existing hydro power. Thus, green labelling of electricity has not yet had a great impact on the growth of new energy technologies.
Assured market shares:	A third way is to reserve market shares for specific technologies or technologies with specific characteristics such as the zero emission vehicle initiative in California or renewable energy portfolio standards. A recent alternative is the system of trade with green electricity certificates that has been proposed in Sweden, Denmark and The Netherlands. Consumers or distributors are obliged to buy a certain amount of electricity from renewable energy sources. When they do, they get a certificate that can be traded. In this way a single market price is established for 'green' electricity. The green electricity quota requirement is then increased over time to reach a specified target. This arrangement is assumed to create a cost efficient introduction of renewable energy in the electricity sector (see Section 5.2 for a critical discussion).
Assured price or subsidy:	A fourth class contains policies that change the cost for investing in specific technologies directly. Green labelling and green certificates are sector specific but normally only technology specific to a minor degree. As is the case with a carbon tax only the most competitive renewable energy technologies will benefit. More technology specific support may come in the form of direct investment subsidies (as for residential solar heating in Sweden), tax redemption (as for the most energy efficient cars in Denmark) or low interest loans (as for PV in the 100 000 roof's programme in Germany). The main alternative to green certificates is the cost-covering rate model that has been used in Germany and Spain where fixed tariffs are paid by electricity distributors for electricity produced by certain technologies, e.g., wind mills and roof-top mounted PV (von Fabeck et al., 1995; Gabler et al., 1997). As in the case of green certificates, the cost of introducing new technologies is spread out as a very small increase of the average electricity price. But in contrast to green certificates this model allows for support of more immature technologies and the fixed price reduce the risk for investors. It has been very successful in promoting PV and wind power in Spain and Germany (Jacobsson et al., 2004; Jacobsson and Bergek, 2002).

There is an old academic debate on the main driver of technical change between proponents for technology push (supply of new technologies) and technology pull (changed demand). This dichotomy now tends to haunt debates over cost efficient climate policy (see, e.g., Schneider and Goulder, 1997). However, studies of the innovation process at the micro-level point out the importance of the linkages and the many feedback loops between technology development and market development (Kline and Rosenberg, 1986).

We argue here that neither R&D funding nor various forms of market stimulus (niche market through special government programmes or mass market through carbon taxes, or both) are effective on their own. Without substantial R&D there will be no technologies that may gain from market creation and without market creation, emerging technologies will be unable to gain from economies of learning and scale. When the technology is adopted and diffused on a niche market new entrants will supply more resources to R&D that in turn will enhance the technology and enable more widespread diffusion.

There are also feedback loops between the adoption of the technology and institutional change. R&D investments will create knowledgeable technology proponents and market diffusion will increase the number of actors, the size of economic interests and the strength of the networks involved.[11] These forces will have an influence on the policy instruments that need to be adopted to sustain the development of the technology to a point of competitiveness and self-sustained growth. For example, in the creation of the German PV industry, the R&D support in the 1970s and 1980s created and increased the strength of various networks that lobbied for the implementation of the federal and local market programmes in the early 1990s. This created in turn an industrial interest, a political awareness and a technological maturity that laid the ground for the more forceful market creating policy instruments that were implemented in 1999–2000 which now, to close the circle, channel private money into PV research and increase the political power of the PV industry (Jacobsson et al., 2004).

It is not only the combination of different kinds of policy instruments that is important but also the timing of intervention. Funding of network formation at a time when the emerging technological system is mature enough to form its own networks is pointless. Funding

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[11] The role of such 'advocacy coalitions' in the development of renewable energy in Germany is thoroughly discussed in a forthcoming paper by Jacobsson and Lauber (2004).

demonstrations at a time when the technology already is well demonstrated may be a way of demonstrating good will when the courage to either support the formation of proper niche markets or throwing the technology in the dustbin is lacking. Likewise, spending more money on basic research when more would be learned from manufacturing research and real world applications is wasteful, but probably less so than the launching of large market introduction programmes and subsidies at a time when the performance still is too poor.

Policy needs not only to be balanced and timed, it also needs to be stable and predictable over long time periods. It is a challenge for a political system with frequent shifts of government to ensure stability and predictability over more than 3 or 4 years. Alas when a lack of understanding of the time lags involved in technical change could create disappointment among politicians, industrialists and the public, which in turn could reduce the interest and support for emerging technologies. Inconsistency in funding could lead to a loss of technological capability. In the early phases the key knowledge is carried by a minor group of people, researchers, small and vulnerable firms or small and vulnerable departments of large firms. Even though some of the knowledge gained in such a group can be codified in papers and patents, important parts of the knowledge (or know how) is tacit. The capability of the United States wind industry was sharply decreased when the market support programmes ended in the late 1980s (e.g., skilled engineers and firms with experience left the industry, Norberg-Bohm, 2000). It takes time to rebuild the capability and thus the development and diffusion process is prolonged even further.

An understanding of the complex process of technical change and its time lags as well as a broadly shared vision of a carbon neutral society is elemental to form balanced, timed and stable policies.

3.4. *Maintaining technological variety*

In speeding up the rate of technical change and development of new technologies, it is important to observe that there is a risk of going in the wrong direction, i.e., picking the wrong winners. It is important to notice that all policy alternatives, including non-intervention, will create winners and losers.

A technology that gets a head start may gain from positive feedbacks (see Section 2), increase its cost and performance advantage, and thus lock out its competitors. Variety is reduced and a dominant design is created (Abernathy and Utterback, 1978; Utterback, 1994). It does not have to be the technology that has the largest development potential that is selected and locked in (Arthur, 1988, 1994; David, 1985).

If a path that for some reason turns out to be a dead end is chosen, valuable time may be lost in two ways: (i) technologies with larger potential have then not been able to gain from increasing returns to adoption and their diffusion on the large scale is therefore postponed. In the worst case there will be ‘organisational forgetting’, i.e., knowledge that is not codified is lost when firms and skilled people give up on a technology (Grübler, 1998). (ii) The early diffusion of a dead-end technology may change the selection environment, in terms of technological interrelatedness, vested interests and bounded rationality, in such a way that it will be even harder for other technologies to enter at a later point in time. In the words of Kline and Rosenberg (1986), “…through inertia of ideas, dollars, or people, the force of prior commitments may keep the project from changing path when it should”. The choices that are made today may decide the technological path for decades to come.

A historical example of this could be the nuclear saga. Among the many nuclear reactor designs suggested in the 1950s, a sequence of events turned the LWR into the dominant design (Cowan, 1990), today accounting for 90% of installed reactor capacity (World Nuclear Association, 2003). The LWR became locked in although its technical and economic advantages were by no means clear. In the early 1970s Alvin Weinberg wrote: “I am still a bit surprised at the enormous vogue of this reactor type for civilian power” (Weinberg, 1972). Nuclear power’s contribution to world energy supply is today far below the hopes and projections made in the 1970s. It has been suggested that nuclear power could have met a brighter future if a different trajectory had been chosen (Lidsky, 1991; Lidsky and Miller, 1998), but that it is now difficult to change track: ‘The first generation of nuclear power has been rejected, but it has left behind a complex matrix of truth and perception. Its successor will not be determined on the basis of simple technological considerations. The ghost image of the first generation remains, even though the active participants have retired from the scene’ (Lidsky, 1991).

It is conceivable Lidsky was wrong and that not only the LWR was a dead end on the nuclear path, but also that the nuclear path as a whole was a detour that has delayed and prolonged the introduction of modern renewable energy technologies. In the early 1950s, also renewable primary energy sources such as wind and solar energy were suggested as equally viable alternatives to fossil fuels. Woytinsky and Woytinsky (1953) looked half a century into the future and suggested that wind, solar and nuclear energy could come to contribute to about 7% of world energy supply each in the year 2000. The guess turned out to be fairly correct for nuclear but not for wind and solar. One reason for this could be that nuclear energy received the lion’s share of government support. In the USA, e.g., nuclear energy received more than 95% of the federal subsidies given to

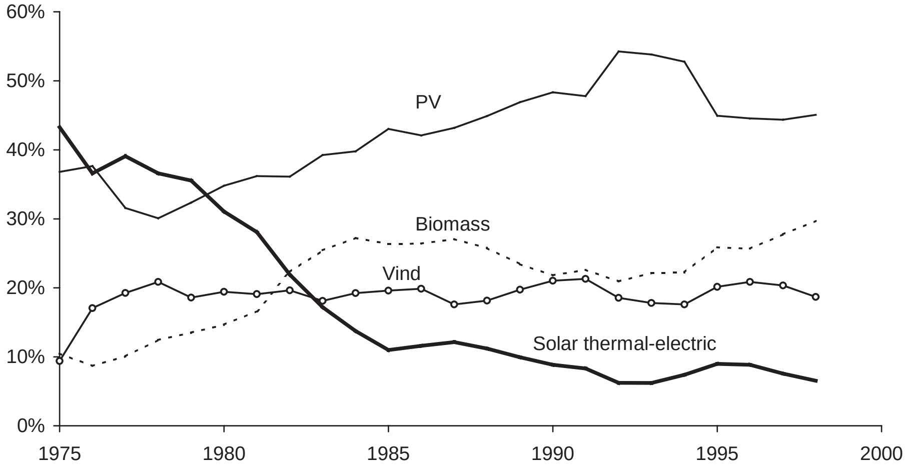

Fig. 4. Relative shares of public RDD funding of four groups of renewable energy technologies in OECD countries (3-year moving average). *Source*: IEA (2001).

the three technological options in the period 1947–1999 (Goldberg, 2000), and the proportion were even higher in other countries. In addition, a number of mechanisms reinforced the nuclear trajectory at the expense of other technologies. Kaijser (1992), e.g., describes how the state-owned power board in Sweden controlled electricity prices to discourage municipal energy companies to invest in co-generation plants. Bergek and Jacobsson (2003) explain the failure of wind power in Sweden partly by a "nuclear power trauma". Wind power did not get any legitimacy since it was regarded as a challenge and not as a complement to the nuclear path.

The specific with maintaining variety and avoiding premature selection in the context of climatic change is that a number of technologies with large-scale potential need to be ready to start to grow very quickly in less than two decades. However, during the coming two decades technologies that are promising in the short term but constrained in the long term on the large scale may benefit from dynamic scale and learning effects and lock out the longer term best options. Menanteau (2000) suggests, e.g., that the dominance of crystalline silicon PV locks out thin-film designs that could have larger potential of reaching low costs. In addition, Andersson and Jacobsson (2000) suggest that in the medium term most promising thin-film designs could be constrained in the longer term due to their requirement of scarce metals.

An important task for policy is thus to sustain variety of technological capability, or 'technodiversity' to reduce the risk of a premature lock-in to one design and thereby reducing the risk of reaching a new dead end. We return to the risks of premature selection in the subsequent section, when discussing the EU biofuels directive and targets for renewable electricity production.

In this respect, current public R&D trends point in different directions. Among renewable energy technologies public funds are directed towards technologies that are closer to commercialisation (Fig. 4). Wind power and biomass are increasing their shares of renewable energy research budgets, probably because these technologies are already competitive or on the verge to become competitive on several markets. For PV a number of commercial niche markets exist and larger niche markets are within sight. In contrast, the share of solar thermal power, a technology with huge long-term potential but with few niche markets available, is decreasing. Further, R&D in the solar electricity technologies are concentrated to a few countries while biomass, wind and solar thermal heating and cooling is more widely spread out amongst different countries (Fig. 5). This makes the longer-term solar options more vulnerable to single political decisions. In contrast to this focus on short-term options when it comes to renewables in general, the variety of competing PV designs that gains R&D support appears to be increasing (Jacobsson et al., 2004).

It is important to balance the speed of change with sustained variety but it will become costly to sustain variety when the emerging technologies start to diffuse on larger scales. Thus, it makes sense to devote some effort on *technology assessment* to at least avoid that all investments are channelled into technologies with limited potential (Andersson, 2001; Sandén, 2004). In addition, *negative environmental and social externalities* besides carbon emissions need to be taken into account at an early stage.

Even though we throughout this paper use terms such as the long-term best options and technologies with large potential it is dangerous to be very specific of which these technologies may be. Technology assessments will never be able to take into account all aspects. The fast breeder nuclear reactor (FBR) was once thought to be the best long-term option because it makes better us of the scarce uranium resource. The LWR was seen as a step, or bridging technology,

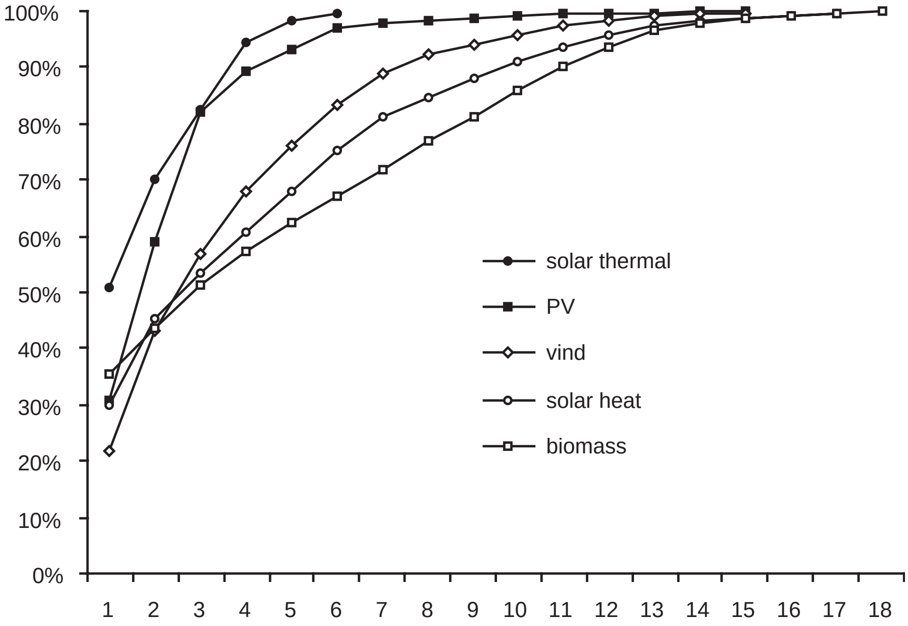

Fig. 5. Concentration of R&D in 1999. The graph should be read as follows. The two countries that invest most RD&D in, say solar thermal, invest 70% of the total OECD RD&D investments in solar thermal. *Source*: IEA (2001).

towards the introduction of the FBR. However, the LWR–FBR trajectory was halted long before any resource constraints were eminent, because of problems with safety, security, technology and public acceptance (von Hippel and Jones, 1997).

An example from the recent history of wind power industry shows that even if the assessment picks the most efficient technology in terms of potential, the shortest way to get there may be via other technologies. Bergek and Jacobsson (2003) conclude that a major reason behind the failure of the Swedish wind programme was that only one design type, large wind turbines, was supported. A similar conclusion of the US failure in wind power development was made by Norberg-Bohm (2000). Firms in Denmark and Germany, where a larger number of actors and designs were supported and learning could be reaped from the diffusion of small-scale wind turbines, now dominate the world market. Ironically, the commercial windmills are now approaching the size that was targeted in Sweden and the US two decades earlier.

Technologies that are constrained or have low potential in the longer term may thus not necessarily lead to dead ends but could act as *bridging technologies* that pave the way for technologies with greater potential. For technological systems with many interrelated components, bridging or hybrid technologies often form pivotal intermediate step. A new technological system is born within the old and often needs to make use of the old system to grow (Freeman and Perez, 1988; Kemp, 1994).

To conclude: Technical change is complex and uncertain. To avoid premature lock-in to technologies with limited potential or negative consequences it is crucial to have long-term strategic thinking and investments in a broad variety of technological options.

4. Three topical policy proposals and their impact on technology development

As described above a useful distinction when it comes to environmental policy instruments is that between economy wide instruments, which aim at bringing down CO_2 emissions (or any other pollutant) through the economy, and technology-fostering instruments, which aim at bringing new technologies to the shelf. The first type aims at large-scale substitution and is bound to involve larger economic transactions. Cost-efficiency is therefore important. We suggest that such policies should be as general as possible to avoid large-scale inefficient allocation of resources. A general carbon tax, or a carbon cap-and-trade system, is a good example of such policies.

The second type aims at developing a range of emerging technologies that vary in costs and characteristics and that starts from low levels of adoption and maturity. Creating competition between these infant technologies may be counterproductive and lead to a premature selection. Instead we suggest that policies of this type should be as technology specific as possible.

In this section, we will discuss three recent international environmental policy proposals in terms of how they contribute to technology development and cost efficient technology substitution. We will, in turn, analyse the idea that carbon emissions trading should be constrained so as to spur technical change in certain regions of the world, green certificates and EU's biofuels directive.

4.1. Carbon trading in the Kyoto protocol

The role of carbon trading[12] in the Kyoto protocol has been a very contentious issue. In the debate following the signing of the Kyoto protocol, the US argued against any constraints on their use, whereas the European Union argued in favour of the so-called supplementarity principle, i.e., that a quantified part of the carbon abatement should be carried out domestically. These diverging views caused the negotiations in The Hague to collapse in November 2000. That very month, presidential elections in the US brought George W. Bush to power in the US, and a few months later he withdrew from the protocol. Currently, there are no quantified supplementarity constraints, and perhaps somewhat ironically, the US got as much flexibility into the protocol as it required in the first place.

The arguments in favour of unconstrained use of the flexible mechanisms receive strong support from economists (see, e.g., a special issue of the Energy Journal, Weyant, 1999). The argument in favour is based on cost-efficiency considerations.

Counterarguments tend to be more subtle.[13] As mentioned earlier, Kyoto is only the first step towards more stringent targets. Therefore, judging a policy (free emissions trading versus a constrained trading regime) on the basis of its near-term cost-efficiency without analysing how this constraint affects technology development misses the point, in particular in light of the fact that most energy-economy models used to support full flexibility treat technical change as exogenous, i.e., technical change is treated as manna-from-heaven (see Azar and Dowlatabadi, 1999, for a review).

In reality, and as argued in the rest of this paper, technical change is the result of the economic environment (prices, expectations, R&D support, subsidies, etc.). For that reasons, models with exogenous technical change do not capture the value of the fact that more advanced technologies might be developed in the supplementarity case.

One argument in favour of supplementarity thus runs in the following way: if there are constraints on trading, the higher marginal abatement cost (in some regions, say country B in our example above), will put stronger pressure on the development of more advanced new technologies. In Norway for instance, it was argued that the only way to meet the Kyoto protocol and at the same time expand electricity production was to develop natural gas fired power plants with carbon sequestration. However, it is clearly less costly to buy emission permits from countries with lower marginal abatement costs, and this is what the Norway is most likely to do. A constraint on emissions trading could thus offer stronger incentives to develop more advanced technologies than a full flexibility case. The development of these more advanced technologies has a value for future commitment periods.

How should we assess supplementarity versus full flexibility with all this in mind? It is our view that it might be preferable to choose specific policies to spur technical change rather than to increase the overall pressure by putting a cap on the use of the flexible mechanisms. This stems from our earlier observations that (i) the more advanced technologies are currently far from the shelf or far from being competitive on the market regardless of whether the carbon tax is 20 or 100 USD/ton C, and (ii) specific policies (such as R&D support and niche market creation) are required to get these technologies going. Limiting emissions trading so as to increase the permit price is hardly an appropriate way to create niche markets for the development of more advanced technologies. Clearly, higher carbon prices would offer more incentives for technology development, but it would most likely be more costly than pursuing technology specific policies. This argument has also been advanced by Victor (2001). Also, if the carbon price were too high at an early stage, then it would create large markets for semi-commercialised technologies that just happens to have an advantage at the moment, but that might not have any major long-term prospects. This might delay the transition to the more promising technological options.[14,15]

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[12] Carbon trading in the Kyoto protocol is generally referred to as the flexible mechanisms and include emissions trading (between Annex-1 countries, i.e., the group of countries that have quantified emissions targets), joint implementation (joint projects between Annex-1 countries) and the Clean Development Mechanism (joint projects between Annex-1 countries and countries in the developing world, which do not have emission caps).

[13] Woerdman (2002) have put forward 16 hypotheses aiming at explaining why the EU was arguing strongly in favour of supplementarity. These hypotheses were then tested empirically by analysing official documents by the commission and by sending enquiries to officials representing either the commission or the member states. The technology innovation hypothesis was one of the more important arguments. The other arguments, e.g., related to equity and compliance in subsequent abatement periods, are not addressed in this paper explicitly.

[14] An additional argument, not related to the specific question of how to get more advanced technologies going, but nevertheless pertinent to the discussion about climate policies and technological change in general, is that of the impact of supplementarity on countries with lower ambitions. Supplementarity means that certain regions will face less or no carbon abatement policies at all, and this means that there will be less pressure to change the energy system in those regions.

[15] There might, nevertheless, be special cases where supplementarity is warranted, e.g., if there is too much "hot air" in the trading regime or if one believes that it is important that individual countries can move ahead and become role models for others (e.g., introducing a carbon price that is higher than what governments in other countries think would be accepted by the general public and thereby show that stringent climate policies are feasible).

4.2. Green certificates and renewable energy portfolios

The use of green certificates and renewable energy portfolios is a way to increase the share of renewable electricity (see Table 4). In this way a single market price for electricity from renewable energy sources is created. There is nothing inherent in this policy that guarantees a cost-efficient way of reducing CO_2 emissions. Rather, the defenders of this policy argue that the key purpose is to create incentives for a cost efficient introduction of renewable energy in the electricity sector. "Let the market, and not the governments, pick the new technologies" goes the argument. However, since the policy is only technology specific to a limited degree, electricity from renewable energy sources, only some alternatives are likely to benefit and others risk being locked out. This may in general be good, but the problem here is that it creates a competition between technologies that are at vastly different levels of maturity. Technologies that are almost competitive may thus out-compete less developed technologies even if the latter have better long-term prospects.

In Sweden, e.g., there is a risk that the recent introduction of green certificates will only create minor incentives to invest in wind for many years since electricity from biomass combustion will be less expensive. In comparison, the technology specific prices for electricity from renewable energy technologies in Germany currently generate a rapid growth of both wind power and solar PV. Thus, policy proposals such as green certificates need to be complemented with specific technology policies aiming at, for instance, solar cells, onshore and off shore wind, etc. at least when such technologies are too far from being competitive.

4.3. Biofuel directive

The European commission has proposed a directive stipulating a mandatory increase in the use of biofuels in the transportation sector (EU, 2001). Here, we analyse this proposal exclusively in terms on its impact on new technologies that might contribute to more substantial CO_2 emissions reductions in the long term. In doing so, we disregard from the fact that the proposal also aims at addressing security of supplies concerns.

A first and important observation is that the carbon reductions that would be achieved in this manner are expected to be substantially more costly than the marginal abatement cost required to meet Kyoto. Thus, the directive should be seen as a step away from cost-efficiency in order to prepare the way for long-term objectives (including not only carbon reductions but also energy security concerns).

However, this does not necessarily mean that it is a well-balanced and appropriate tool to provide incentives to develop appropriate long-term technologies for the transportation sector. First, the proposal does not make a distinction between different kinds of biofuels. This means that it is primarily the fuel that has the potential to reach low costs in the near term that will gain momentum by the proposal. However, it is by no means clear that this is actually the technology that is cost-effective in the long run. This means that we might get locked in to an inferior technology to early.

Second, if ethanol from grain or ethanol produced from tropical sugar cane, becomes the choice of fuel, no major learning effects can be expected, because these technologies are commercially mature and available at a large scale (11 billion litres in Brazil from sugar cane, and 7 billion litres of ethanol from starch crops, mostly corn, in the US, in 2002, Kingsman, 2003).

Third, there are reasons to believe that biofuels might not play a major role in the transportation sector even if stringent carbon abatement policies are adopted. Biomass can be expected to be more cost-efficiently used for heat and electricity generation than if converted into transportation fuel (see, e.g., Azar et al., 2003). The reason for this is that the potential supply of biomass is limited (see Berndes et al., 2003) and that the conversion efficiency of biomass into liquid fuels is low compared to using biomass for heat. Instead, hydrogen from solar, and from fossil fuels with carbon capture and storage (and from biomass) is a more likely long-run choice of fuel in the transportation sector.

Finally, this does not mean that we should not pursue policies to reduce CO_2 emissions from the transportation sector. Clearly, there should be a carbon price as large as in any other sector, but it is probably premature to let a created market select among alternative fuels. Rather, variation or 'technodiversity' should be promoted. Although an earlier analysis of ours (Azar et al., 2003) strongly suggests that hydrogen will be the key fuel for the future, research efforts, including minor market experiments, should also continue on a number of technologies for alternative fuels production and use, e.g., ethanol from woody biomass, thermochemical gasification of woody biomass for the production of methanol, DME and FT liquids. There may not only be important niche markets where these fuels might thrive in the future. Major unforeseen drawbacks with the hydrogen future may also materialise.

5. A low cost policy proposal for radical technical change: the decade of great experiments and failures

To change the selection environment in favour of CO_2-neutral technologies, the price to those who emit carbon dioxide needs to be raised. But as we have argued, this is not enough. To reach deeper reduction targets in the long-term new technologies and energy infrastructures that currently are not commercially available or far from competitive on energy mass markets need to be implemented. Many technologies are proposed, but today we cannot tell which will prove to be the best long-term solutions. Hence, a variety of technologies need to be fostered. The key issue is learning. We therefore propose that the coming decade should be the decade of great technological experiments and failures. Let, if not a thousand, at least a hundred flowers bloom!

It should be noted that a programme of great experiments and failures might be rather inexpensive in comparison to estimated overall costs of meeting the Kyoto protocol. Finding the optimal level of public RD&D funding is clearly an elusive objective. It is very difficult to rigorously quantify how much ought to be spend on public RD&D on alternatives (an attempt along these lines is offered by Schock et al., 1999).[16] It is sometimes argued that the revenues from a carbon tax, or the auctioning of permits, should be redirected into public and private RD&D on alternatives. However, the revenues that would be raised are enormous compared to current energy public RD&D expenditures. A tax equal to 70 USD/ton C (as might be required to meet Kyoto, with the US onboard) would raise 400 billion USD/yr if applied worldwide.

A more modest proposal would be that 1 USD/ton C levied in all countries is redirected into RD&D. It would raise revenues corresponding to 6 billion USD, i.e., almost the entire OECD public investments in energy RDD and 10 times the investment in RD&D on renewable energy. This is important since a 1 USD/ton C would not change energy prices noticeably (coal prices would increase by less than 0.02 USD/GJ, electricity prices would increase by 0.02 US cents/kWh and gasoline cost would "jump" by 0.06 US cents/l). The purpose here is not to suggest that it should be exactly 1 USD/ton C, but rather highlight the fact that a tax with an almost unnoticeable impact on energy prices might generate revenues that can multi-fold current public R&D expenditures on energy.

RD&D policies should be complemented with policies that create markets. To avoid a premature lock-in these should be technology specific.[17] Here, we propose that all kinds of subsidies or technology specific policies should be made contingent upon the following conditions: (a) they should set in motion a process of self-sustained growth, driven by dynamic learning and scale effects, where cost reductions generate market growth which in turn generate cost reductions. (b) the subsidised technology should have good prospects for capturing future markets. Subsidies should therefore decrease over time and the scale of the niche markets made available should be in proportion to the needs of the new technology.

Dynamic scale and learning effects tend to reduce the cost of new technologies as their market shares grow, so the overall costs of a subsidy does not have to become prohibitive. Fig. 6 provides an illustration of the annual costs of making PV competitive.[18] In the example the PV capacity is assumed to increase by 30% per year to reach 14% of OECD electricity production in 2030. The increased cumulative production is assumed to decrease cost at a rate set by the progress ratio (PR) of the experience curve.[19] The subsidy cost is calculated as the difference between the actual investment cost, starting at 6 USD/Wp in 2000, and a target cost of 1 USD/Wp (for a PV system).[20] This target cost roughly corresponds to 4–8 US cents/kWh, depending on solar irradiation, which would be competitive with coal based electricity given a cost of carbon dioxide emissions of 70–100 USD/ton C. The literature suggests historical PRs of 0.77–0.82 for PV modules (Parente et al., 2002). If a PR of 0.80 for PV systems is assumed, the cost of the subsidy peaks at 9 billion USD/yr in 2016. If the cost is spread out on the electricity production in OECD countries, it corresponds to an extra cost of 0.1 US cents/kWh.[21] This is a small figure in comparison to some currently existing subsidies to conventional energy. The nuclear R&D budget in Japan has since 1980 amounted to about 0.3 US cents/kWh of all electricity generated in Japan (Fig. 7).[22] The German coal subsidy in 2002 amounted to about 1 US cents/kWh of all electricity produced in

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[16] In short they derive their results from subjective probabilities that we have to meet a various stabilisation target, estimates of the costs of meeting various stabilisation targets and subjective probabilities that a certain R&D programme will reduce these costs with a certain probability. For instance, assume that there is a 20% probability that we have to meet a 450 ppm target, and that there is a 20% probability that an ambitious R&D programme would reduce the net present value cost of meeting this target by half (say from 5 to 2.5 trillion USD). Then the expected value of the R&D effort is $2.5 \times 0.2 \times 0.2$ trillion = 1 trillion. If the discount rate is 5%, the annuitised cost is roughly equal to 50 billion USD/yr, i.e., substantially higher than current investments in R&D. Although interesting as exercises, these numbers are clearly very sensitive to the assumed probabilities.

[17] It should be noted that the term 'technology specific' is inherently relative. Separate markets cannot be made for every technological subtype. The support for specific designs within technological families needs to be taken care of by RD&D instead of market creation policies. The key issue here is that technological families should not be made too broad. In our view 'electricity from renewable energy" or 'biofuels' are families too broadly defined. See Sandén (2004) for a discussion.

[18] For more details and elaborations see Sandén (2003).

[19] If the PR is 0.80 the cost decrease by 20% per doubling of cumulative production.

[20] If we modelled a subsidy system based on fixed prices per produced kWh (as in Germany today) instead of investment subsidies, the annual cost would initially be lower, the peak cost would also lower but the cost would prevail a number of years after that new systems could be produced at competitive costs.

[21] Electricity production is assumed to grow by 2% per year.

[22] In 1998 the nuclear R&D expenditure amounted to more than 0.8 US cents/kWh of electricity in nuclear power plants!

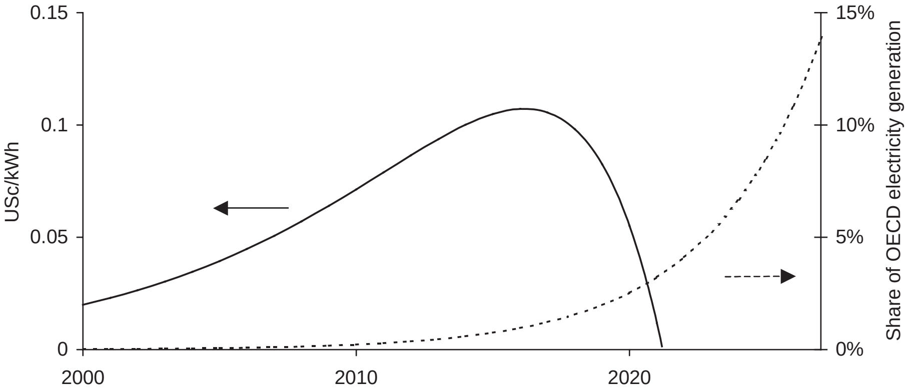

Fig. 6. The cost of a PV subsidy given as additional cost per kWh of OECD electricity generation. The cost peaks at 0.1 US cents/kWh. The curve to the right indicates PV's share of OECD electricity generation in the scenario. See text for other input data. *Source*: Sandén (2003).

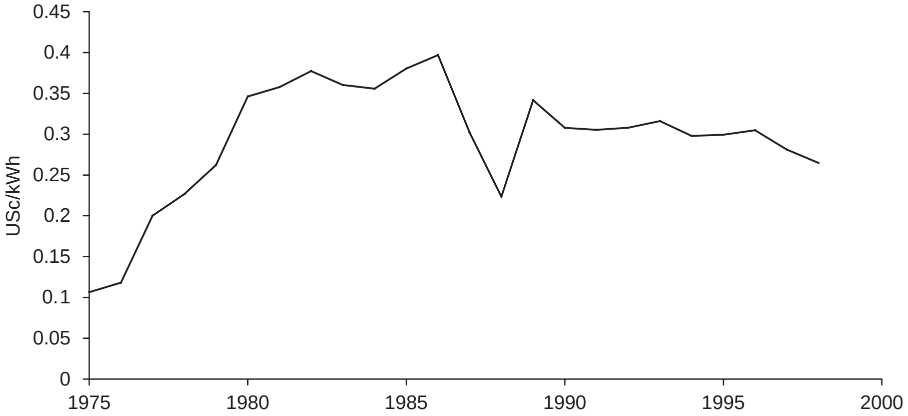

Fig. 7. Cost of the public Japanese nuclear RDD budget per kWh of the electricity consumption in Japan (nominal value).

Germany,[23] an annual subsidy 10 times (!) larger than the peak in the estimated required subsidy scheme to make PV competitive.

With no ambition of presenting a complete list the following examples could make the hundred-flowers-bloom strategy more concrete. The bill is likely to fall below 10 GUSD/yr, i.e. an order of magnitude below estimates of the cost of implementing the (full) Kyoto protocol.

In the coming 10 years a continued market expansion of more than 25% per year for wind power and solar PV is ensured. A broad range of PV materials should be tested and commercialised. Building integrated solar heating becomes the standard solution for water heating in new buildings. Ten 100 MWe solar thermal power plants of different kinds are built. Direct solar hydrogen production is heavily researched. Ten large-scale demonstration plants for CO_2 sequestration are built (with different technological approaches being tested). CO_2 storage in different geological settings is tested. Gasification of biomass for electricity and synfuel production is commercialised. Technologies for hydrogen storage is heavily researched and demonstrated. New natural gas pipelines are made compatible with hydrogen. Ten cities have fuel cell bus fleets and houses with no external heating systems are extensively demonstrated in many countries in cold climates.

Variety is the key element of the hundred-flowers-bloom strategy, not only variety when it comes to support of technologies but also when it comes to support of actors. Our suggestion should not be viewed as a demand for a massive increase of high-tech research centralised to a few big labs or companies. Rather, accepting the fact of carbon lock-in, we think it is important to acknowledge that we in many cases have to start with seeds and fragile small plants rather than trees. This requires different skills from the gardeners. We believe it is important that different technologies are fostered on an appropriate scale and that different kinds of actors are given more incentives to innovate, from small entrepreneurs to large enterprises, from basic science to craftsmen. Feedback loops between technology development, market diffusion, institutional change and strengthening of new actor networks can then create the required innovative climate in the garden of technology.

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[23] 2 € cents/kWh of electricity from coal (Jacobsson and Lauber, 2004).

6. Conclusions

In this paper, we have analysed policies to promote technical change in the context of climate change. We began with the proposition that near-term climate policies should recognise four objectives: near-term abatement, institution building, technology development and the strengthening of proactive actors. The Kyoto protocol addresses all four but we also observed that the protocol could most likely be met by an increased use of commercially available technologies, e.g. biomass, wind, solar thermal heating, increased energy efficiency and natural gas instead of coal.

However, beyond 2030 more advanced technologies will need to be deployed at a large scale if we are to avoid serious climatic risks. These technologies include, e.g., solar electricity and solar hydrogen generation technologies, carbon sequestration, hydrogen storage and fuel cells for transportation, electricity generation and distributed combined heat and power generation. There is a risk that the society in its quest for cost-efficiency in meeting near-term emissions target, becomes blindfolded when it comes to the more difficult, but equally important issue of bringing more advanced technologies to the shelf.

A two-pronged strategy is needed. First, in order to meet near-term targets, such as those of the Kyoto protocol, economy wide price incentives (a tax or a cap-and-trade system), will most likely bring about the technological changes required to meet the near-term target in a cost effective manner. Here the key impact of the price incentive is that it changes the economic environment by which consumers and companies select technologies from the shelf.

Second, meeting longer-term targets requires complementary technology policies since the carbon prices needed to meet the Kyoto protocol will most likely not be high enough to create sufficiently strong incentives to develop more advanced technologies. Governments need to introduce incentives that support the process of bringing new technologies to the shelf.

A portfolio of instruments, including RD&D funding, support for industry network formation, niche market creation, and institutional adaptation needs to be implemented in a balanced way to foster new industries and set in motion a process of self-sustained growth, driven by dynamic learning and scale effects, where cost reductions generate market growth which, in turn, generate investments and learning that lead to further cost reductions. In addition, this process will increase the strength and numbers of proactive actors. Institutional feed-back loops will materialise as the political power of the new industries grow in relation to the power of groups with vested interest in entrenched technologies, making it easier to negotiate and adopt stricter climate targets in later periods. The two-pronged strategy thus offer an evolutionary escape route from carbon lock-in.

Care should be taken not to make technology-fostering instruments too broad. Limiting the use of the flexible mechanisms in the Kyoto protocol (supplementarity) is probably too blunt as a tool to bring more advanced technologies to the shelf. Similarly, there is a risk that green electricity certificates and the biofuel directive in the EU will only benefit technologies that are close to being competitive. If they are not complemented with more technology specific instruments, more advanced technologies will not be brought to the shelf.

It is important to note that the cost differential between the two types of instruments, economy wide price incentives and technology-fostering instruments, is at least one or two orders of magnitudes. For instance, the annual cost of meeting the Kyoto protocol (with the US onboard) is estimated at around hundred of billions of USD annually (within wide margins). This is at least 100 times the current annual public renewable energy RD&D expenditure in the IEA countries (0.5 GUSD/yr in 2000)! Similarly, we estimated that the cost of a programme to buy down the cost of PV from 6 to 1 USD/Wp, which would make PV competitive with conventional electricity production on most markets, could peak at no more than 1 USD/MWh of electricity in OECD countries (around 1% of the residential electricity price).

The key issue in bringing new technologies to the shelf is learning. We therefore propose this decade to be the decade of great technological experiments and failures. A bold venture on experiments, demonstrations and niche-market formation would make it possible to bring down costs substantially for a dozen of advanced technologies and to understand better which might have good prospects and which have not. If this is not done, it could become politically infeasible to negotiate and adopt more stringent targets in subsequent commitment periods.

Acknowledgements

Chalmers Environmental Initiative, Göteborg Energy Ltd. Research Foundation, FORMAS, Swedish Energy Agency, Preem's Foundation for the Environment and VINNOVA is gratefully acknowledged. We would also like to thank Dean Abrahamson, Per Kågeson, Bert de Vries and an anonymous reviewer for valuable comments on the paper.

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