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Technology Innovation, Development and Diffusion

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FOREWORD

This document was prepared in May 2003 by the OECD and IEA Secretariats at the request of the Annex I Expert Group on the United Nations Framework Convention on Climate Change. The Annex I Expert Group oversees development of analytical papers for the purpose of providing useful and timely input to the climate change negotiations. These papers may also be useful to national policy makers and other decision-makers. In a collaborative effort, authors work with the Annex I Expert Group to develop these papers. However, the papers do not necessarily represent the views of the OECD or the IEA, nor are they intended to prejudge the views of countries participating in the Annex I Expert Group. Rather, they are Secretariat information papers intended to inform Member countries, as well as the UNFCCC audience.

The Annex I Parties or countries referred to in this document refer to those listed in Annex I to the UNFCCC (as amended at the 3rd Conference of the Parties in December 1997): Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, the European Community, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and United States of America. Where this document refers to "countries" or "governments" it is also intended to include "regional economic organisations", if appropriate.

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EXECUTIVE SUMMARY

New technologies will play a critical role in achieving the objective of the UN Convention on Climate Change. Without radical changes in lifestyles, only a massive deployment of carbon-free (or close to carbon-free) energy technologies can power the world economy and satisfy growing energy needs, especially of the developing world, while stabilising atmospheric CO2 concentrations in the long run.

Reduced energy-related CO_2 emissions can be created by technical improvements at different levels and involve:

- End-use technologies in all sectors: household and commercial, industry, transport, which could reduce the amount of energy used
- Fuel switching from coal to oil to gas;
- Increased efficiency of energy conversion (such as power plants and refineries);
- Phasing in non-carbon energy sources, such as nuclear power and renewable energy sources; and
- CO_2 capture and storage.

It is not possible to define what exact mix of these various technologies would best be able to stabilise atmospheric CO_2 concentrations, at what level and for what price. However, excluding any option is likely to make achieving the objective of the Convention more expensive and/or to raise the level of concentration ultimately reached.

Over the next several decades, non- or low carbon-emitting energy technologies are not likely to be competitive with current high emitting technologies beyond some "niche markets", particularly given the relative abundance of carbon-rich fossil fuel resources. However, delaying action until prices are competitive may lead to unacceptably high CO_2 atmospheric concentration levels. Pricing carbon emissions (directly or indirectly – e.g., through quantified objectives) would expand markets for existing and forthcoming carbon free technologies and accelerate their deployment.

Creating markets for new energy technologies is likely to require, on top of carbon pricing, a broad range of measures. Support for research and development is of primary importance – and current levels in most developed countries are likely insufficient. In most cases, however, "learning investments" will have to be spent before full competitiveness can be reached by new technologies.

Governments can and do use a wide number of instruments to promote development and dissemination of new technologies, from subsidising R&D to voluntary agreements, standards, taxes and cap-and-trade systems. Policy mixes may be more efficient than isolated measures.

While quantitative objectives or price instruments may be necessary to achieve short-term emission reductions with the current set of energy technologies, they might not be sufficient to promote the development of new technologies required to achieve the large, long term reductions needed to stabilise atmospheric CO_2 concentrations at any level. Policies focussing on technology innovation and development are thus needed. Conversely, such policies alone are not likely to provide for cost-effective short-term reductions.

International collaboration, which encourages both information and cost-sharing could greatly enhance the effectiveness of policies for technology innovation, development and dissemination. Technology transfer to the developing world is likely to play a critical role in controlling global emissions.

International technology agreements could help support additional efforts to promote technology innovation, development and diffusion. They could complement agreements to achieve shorter-term emission limitation or reduction objectives.

1. INTRODUCTION

New technologies will certainly play a critical role in achieving the ultimate objective of the UN Convention on Climate Change: "stabilising atmospheric concentrations of greenhouse gases." Such an achievement is likely to eventually require near elimination of CO_2 emissions. Without radical changes in lifestyles, only a massive deployment of carbon-free (or close to be carbon-free) energy technologies can power the world economy and satisfy growing energy needs, especially of the developing world, while making stabilisation sustainable over the long term.

While carbon free energy technologies already exist (e.g., nuclear power and renewable energy technologies), they represent only a small share of current and projected future energy needs; fossil fuels continue to dominate the energy mix. Without new policies, the IEA's most recent *World Energy Outlook* (IEA, 2002c) projects this trend will continue in the coming decades.

The AIXG decided in its September 2002 meeting to focus attention on the numerous challenges faced in promoting new and alternative, low and carbon-free technologies. Key issues addressed in this paper include:

- Identifying some key technologies, assessing their maturity and the potential for CO_2 reduction they offer;

- Considering how technological change occurs, illustrating in particular the role of learning-by-doing processes, the role of behaviour and that of policymakers;

- Considering what policy tools governments might use to accelerate maturation and foster deployment;

- Considering what role increased international co-operation and technology transfers could play in fostering innovation and technical changes.

Following a review of these issues, the paper provides a brief discussion of the possible effects of different policy mixes, in particular with respect to the timing of achieving stabilisation. This timing is likely to be critical in determining the level at which CO_2 concentrations might eventually be stabilised (cf. IPCC 2001; IEA, 2002a). Three different strategies are considered: one mainly based on "comprehensive" instrument such as taxes or cap-and-trade systems; one mainly based on increased technology co-operation, and one "mixed" strategy that would incorporate both elements. The conclusion takes stock of these preliminary results and considers future work.

It should be noted that this paper exclusively focuses on energy technologies. It does not consider sinks, non-energy CO_2 emissions or emissions of other greenhouse gases (even if they are energy-related), or technologies for adaptation.

2. TECHNOLOGY POTENTIAL

Energy-related CO_2 emissions can be reduced through technical improvements throughout the energy sector, and involve:

- End-use technologies in all sectors: household and commercial, industry, transport, which could reduce the amount of energy used;
- Fuel switching from coal to oil to gas;
- Increased efficiency of energy conversion (such as power plants and refineries);
- Phasing in non-carbon energy sources, such as nuclear power and renewable energy sources;
- CO_2 capture and storage.

These possibilities are explored in some detail in the Appendix "Key Technologies". The analysis here discusses three policy-relevant issues arising from this information:

- Are existing technologies sufficient to achieve the objective of the Convention?
- Will non-carbon or low-carbon technologies (including fossil fuel use with CO_2 capture and storage) become fully competitive with CO_2 emitting energy technologies soon enough if market conditions are not modified by directly or indirectly pricing the climate change externality?
- Can we already shape a long term, non-carbon energy future?

2.1 Existing and future technologies

There is a range of opinion as to the readiness of existing technologies to reduce emissions. While presenting a range of views, one of the more optimistic conclusions is that of the IPCC, which in the Third Assessment Report, completed in 2001, concluded: *"… Known technological options could achieve a broad range of atmospheric stabilisation levels, such as 550 ppm, 450 ppm or below over the next 100 years or more… Known technological options refer to technologies that exist in operation or pilot plant stage today. It does not include any new technologies that will require drastic technological breakthroughs…"* Other recent publications, while having less standing than the IPCC, emphasize the difficulties. For example Hoffert *et al.* (2002) criticised the IPCC's conclusion as representing a *"misperception of technological readiness."* They instead conclude that there is a need to intensify research on such technologies – a need they suggest is by no means universally appreciated.

Notwithstanding these differences, there is widespread agreement that known technological options exist in energy production, conversion and end-use that could reduce emissions significantly from their business-as-usual trends in the short term and thus be compatible with relatively low levels of concentrations. For this set of technologies, the problem is not development, but how to efficiently disseminate these technologies in all countries. A successful solution to this challenge will likely only emerge with significant reductions in the cost and penetration of existing technologies, as well as the development of new technologies.

Numerous carbon-free technologies already exist. Light water nuclear reactors, wind turbines, concentrating solar and biomass-fuelled power plants, biofuels, photovoltaics are industrial realities[1]. Important technical improvements will still be required, however, to deal with physical and, ultimately, cost constraints. And in many cases, these improvements may be more than incremental: for example, the future of nuclear power may rest entirely with new reactors that could be safer, save resources, produce less hazardous waste and prevent proliferation[2].

The intermittent character of many renewable energy technologies – and costs (for PV at least) – will limit wind or PV expansion (PV today costs more than ten times electricity generated from coal). Concentrating solar plants producing around the clock (using heat storage instead of fossil fuel back-up) might be built in the coming years – but do not exist today. Carbon-free hydrogen production exists on paper, as do hydrogen-fuelled cars and planes – but there is a long road and significant technological challenges between today's dreams and future realities (Appert, 2003). While in the future, hydrogen from renewable or nuclear power might become an option (Barreto *et al*., 2003), in the near to middle term (possibly up to 2050) renewables would more efficiently replace fossil fuels in the power sector than in the transport sector (Eyre *et al*., 2002; Azar *et al*., 2003).

It would be a mistake, however, to believe that technical progress, by itself, always tends to reduce CO_2 and other greenhouse gas emissions. There are numerous examples where technical progress may not necessarily do so; in fact it may even increase or prolong emissions. In the last decades, technical progress has significantly reduced costs in exploration and exploitation of oil and gas. Inasmuch as this has displaced some coal use, it has helped mitigate climate change. However, where it has displaced nuclear power, energy efficiency efforts or renewable energy sources, it has contributed to increasing greenhouse gas emissions.

The current technological portfolio is unlikely to allow reaching the ultimate objective of the Convention, unless the willingness-to-pay is extremely high[3]. Moreover, short-term decisions in this arena might have large long-term implications – and different cost implications for achieving similar concentration levels. Finally, technology change tends to be cumulative rather than resulting from single major shifts. All these factors combine to make the technology dimension of climate change mitigating policies critical in any future effort to meet the Convention's stabilisation objective.

2.2 Competitiveness of non-carbon technologies

It is often believed that climate policies should mainly aim to accelerate the introduction of carbon-free or carbon-lean energy technologies in competitive markets. Implicitly, this view supposes that sooner or later these technologies will become fully competitive on their own merits, and will be able to compete with increasingly scarce carbon emitting fossil fuels. Inherent in this view is that if we support pre-competitive technologies, they can ultimately take over in the market.

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[1] It may be argued that the full life cycle of these so-called "carbon free" technologies still involve some carbon emissions. Building a nuclear power plant or manufacturing PV cells requires fair amounts of energy – and currently this implies CO_2 emissions. This however, reflects the current energy mix. If the proportion of these technologies increases in the energy mix, the production of power generating capacity will progressively involve less indirect carbon emissions.

[2] While various concepts for such reactors have been suggested, industrial developments remain hypothetical only; see IEA et al., 2002 for a more complete discussion.

[3] For example, most macro-economic models project a substantial continued growth in global CO_2 emissions from the energy sector under a business as usual scenario. (see, for example, IEA, 2002c)

This perception tends to fuel the vision that technological change alone is the key to solving the climate change problem. But this vision may well rest on an incorrect perception of market and technology dynamics.

The fossil fuel resource base contains much more carbon than the atmosphere can likely accommodate in a way that would respond to the ultimate objective of the climate change UN Convention. While all conventional oil and gas resources could be burned without driving CO_2 concentrations above a 450 ppm level, unconventional resources and, first and foremost, coal are plentiful and their full use would drive concentrations to very high levels (see, e.g., IEA 2002a, p.44).

Moreover, the fossil fuel industry has demonstrated a great capacity to react to changing energy prices by reducing costs through technological changes. In the early 1980s cost of oil from new deep-water platforms was estimated to be around US $25/bbl. Today such fields are still being developed with production costs of about US $ 10/bbl – thanks to many technical improvements.

Other technology refinements have effectively alleviated– at least to some extent –concerns for the local environment arising from the production and use of fossil fuels. Air pollution has been significantly reduced in all Member countries (either from fuel switching, from fuel cleaning or from end-of-pipe technologies). Environmental regulations have and will continue to add costs to using fossil fuels – although seldom enough to make them costlier than alternatives. “Ancillary benefits” of CO_2 emission reduction strategies must be factored in, but there should be no presumption that fossil fuels will become uncompetitive if local environmental issues are given more weight in the future.

While conventional oil and gas resources inexorably move toward eventual exhaustion, the magnitude of the coal resource suggests that almost any near-term energy future will likely rest (at least in part) on coal, and may well include massive conversion of coal into synthetic fuels. Such technologies already exist and their deployment will likely drive costs down. There is no guarantee that non-carbon sources or capture and storage will ever be fully competitive with coal-based synthetic fuels for transport or home use – and even less with coal-fuelled electric power.

As a consequence, there is no guarantee that strategies focussing on research and development (including dissemination efforts) of carbon-free technologies will necessarily be successful. This is particularly true if technologies are developed under current market conditions rather than with changes in the pricing of climate change externalities. In fact, the level of stabilised atmospheric CO_2 concentrations possibly achieved following strategies focussing exclusively on technological change “push” is unknown.

2.3 Non-carbon energy futures

A growing number of studies undertaken by companies, governments, academics or diverse institutions or NGOs attempt to evaluate long term non-carbon energy futures, either at global level or at country level (for a review of recent work, see IEA, 2002i). An example of ongoing work is the IEA/EU collaborative ACROPOLIS project. This projects is investigating, through the use of fifteen global, regional and national models, policies that might bring about the development and penetration of sufficient low-carbon technologies to reduce GHG emissions. The model simulations explore some possible policy impacts on total energy system costs, total primary energy supply, CO_2 emissions, electricity generation capacity and the share of different technologies in both power generation and energy end-use. The time horizon considered by the models varies from 2020 to the year 2100 (IEA, 2003e).

While this body of work is essentially descriptive, it also has a normative function. By illustrating various and contrasted possible energy futures it suggests that some are more desirable than others – in particular, but not exclusively, in terms of climate change and the environment. Thus, these scenarios might be used to engage policymakers and society at large in a discussion of what the future may look like – or of what the future should look like. Eventually, short-term decisions could be inspired by the willingness to see some of these scenarios become reality – and to avoid the realisation of others.

Scenarios established by governments may be even more normative. For instance, the recent UK's Energy White Paper *"Our energy future – creating a low carbon economy"*[4]clearly sets goals: to put the UK on a path to cut the country's CO_2 emissions by some 60% by about 2050; to maintain the reliability of energy supply; to promote competitive markets in the UK and beyond; and to ensure that every home is adequately and affordably heated. The White Paper, however, does not indicate what the energy consumption could be in 2050, nor does it describe the energy mix of the country at the time. While it provides for some targets in 2010 (e.g. for renewable energy), its energy scenario for 2020 remains qualitative.

In sum, the variety of available scenarios, as well as the information reviewed in the Appendix, suggest that there is no uniquely valid technology path for a given energy and environment future. However, future work could include the building or the review of various and contrasted indicative scenarios.

[4] Available at: http://www.dti.gov.uk/energy/whitepaper/index.shtml

3. TECHNICAL CHANGE

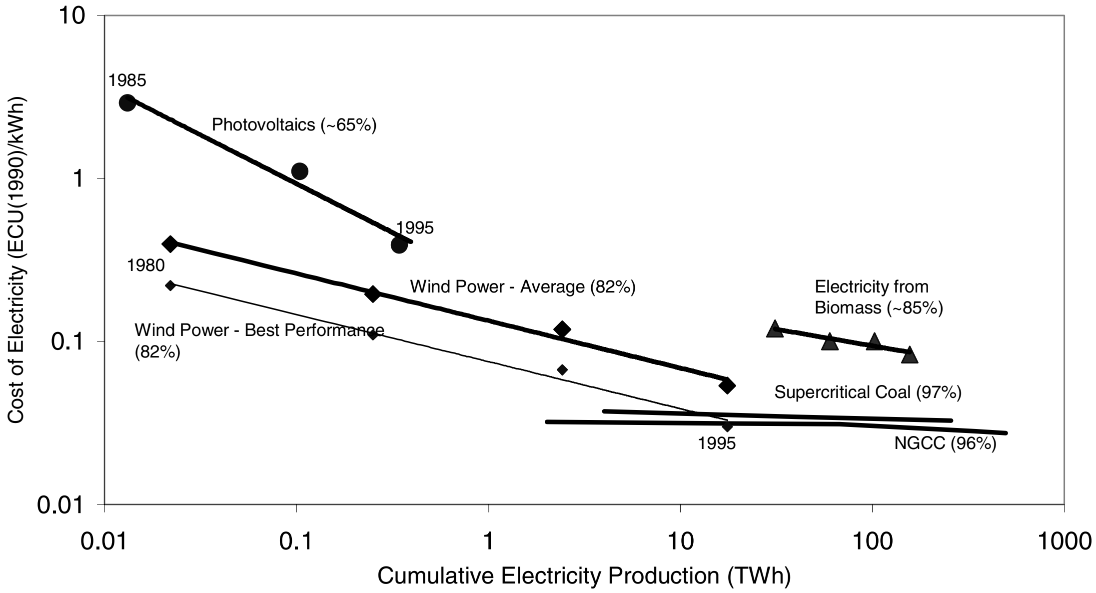
3.1 How technologies evolve

Schumpeter (1942) distinguishes three stages in the process by which a new, superior technology permeates the marketplace. *Invention* constitutes the first development of a scientifically or technically new product or process. *Innovation* is accomplished when a new product or process is made available on the market. *Diffusion* (or dissemination) is the process that sees a successful innovation gradually coming to be widely available for use in relevant applications through adoption by firms or individuals. The cumulative economic and environmental impacts of new technology results from all three of these stages, which we refer to collectively as the process of technological change. (Jaffe *et al*., 2002).

However, these definitions might wrongly suggest that technical change is a linear process that simply goes from invention to innovation to diffusion. In fact, it is more a cyclical process; the feedback between market experience and further technical development are especially important. Market prospects are the most vital stimulant of industry research and development (R&D) and the deployment of technologies is a key source of information on them. Market development and technology development go hand in hand (IEA, 2003).

The view that technology deployment in the marketplace – not only research and development efforts – is a key element to speed up technical change, is borne out by lessons from past technological developments. They reveal that the costs of technologies decrease as total unit volume rises. A metric for such change is the "progress ratio", defined as the reduction of cost as a consequence of the doubling of cumulative installed technology. This ratio has proven roughly constant over time for individual technologies – although there is considerable variance in the ratio between technologies. The fact that the progress ratio is usually constant means that technologies learn faster from market experiences when they are new than when they are mature. The same absolute increase in cumulative production has a more dramatic effect at the beginning of a technology's deployment than it has later (see IEA, 2000). This is why new techniques, although more costly at the outset, may become cost-effective over time if they benefit from sufficient dissemination. Figure 1 below shows this phenomenon in the power-generating sector.

Figure 1. Electric Technologies in EU 1980-1995



Numbers in parenthesis are estimates of progress ratios. They indicate the change in cost when market size doubles. Thus, for example, if the size of PV markets double, the cost of PV electricity is reduced to 65% of its previous value.
Source: Source: IEA, 2000

Projecting forward using concepts of learning-by-doing is risky; there is a clear indication that some mature technologies no longer follow the progress ratio of their early development. However, the concept may well be robust for many of the new, immature technologies such as renewable energy. Using these ratios, it is possible to gain some idea of how competitive advantages may change with time. For example, in photovoltaics, a break-even point with fossil fuels might be expected around 2025 if historical growth of PV deployment at 15 per cent per year continues. The difference in price between these technologies and least cost options constitute “learning investments” – cumulative costs for supporting new technology. The area under each curve (or line) can be used as a rough estimate of the total capital investment required to bring the technology’s cost down to a certain level.

Much of the progress in PV growth is supported through niche markets – in remote places where photovoltaics are already the most cost-effective solution. In the case of wind power, market deployment has increased in a number of countries where policies drive consumers to pay extra for wind power. The US in the 1980s, and Denmark in the 1990s were the main leaders, and more recently Germany, Spain and India have seen extensive growth in wind generation. Whether these technologies can continue to have rapid increases in cumulative capacity will in part depend on their moving from small niche markets to more mainstream application.

Distinguishing the effects of R&D efforts and those arising from market deployment may not be easy, as Clarke & Weyant (2003) point out. Learning curves literature usually misses a detailed history of R&D expenses, while R&D literature often ignores learning effects. Moreover, the coexistence of increased market shares and decreased costs does not necessarily demonstrate that the former caused the latter. The causality relationship works both ways: when cost decrease, niche markets increase.

3.2 Path dependence

This feedback process from markets to technical improvements, creating increasing return, has numerous consequences. It tends to create "lock-in" and "lock-out" phenomenon: it is not because a particular technology is efficient that it is adopted, but rather because it is adopted that it will become efficient (Arthur, 1989). Technological paths often depend on initial conditions. Thus, technologies having a small short-term advantages may "lock-in" the technical basis of a society into technological choices that may have lower long-term advantages than others technologies, which are consequently "locked-out".

The systemic and cumulative nature of technological change leads to clustering effects, or technological interdependence, and possible phenomena of increasing returns: the more a technology is applied the more it improves and widens its market potential. Change is directionally persistent based on an accumulation of past decisions. As noted by Roehrl and Riahi (2000), "*technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to change its course.*"

However, trends are neither immutable nor infinite: increasing returns might be bounded and scale economies exhausted. Entrepreneurs facing new pressures may break technology barriers, and technologies that lost out in early competition may subsequently become successful. For example, while electric cars seem to have lost the battle against internal combustion engines a long time ago, they might be given a second chance – although their competitors now benefit from about a century of technical improvements.

Several policy conclusions may be drawn from this analysis. The first is that redirecting technical change in order to reduce CO_2 emissions has to build on "learning-by-doing" processes. Laboratory research and development efforts are unlikely to be sufficient to produce sufficient progress so as to impose new technologies on competitive markets in one shot. As detailed below, creating markets for new energy technologies necessitates broader efforts.

Another, no less important policy conclusion, has to do with the timing issue. As pointed out by Roehrl and Riahi (2000), "research, development and demonstration efforts as well as investment decisions in the energy sector over the next two to three decades are critical in determining which long-term technological options in the energy sector may be opened, or which ones may be foreclosed".

3.3 Technological and behavioural change

Another dimension of the debate on technology in mitigating climate change relates to the important role that behavioural change can play in reducing emissions. For some, technical change should simply suppress emissions, and nothing else should change. For others, there is almost no need for new technologies, as changes in behaviour could accomplish large emission reductions. These extreme and opposite views are further detailed below.

3.3.1 Two polar views

The role of technology versus that of behaviour may be characterised (and caricatured) in two polar views. According to the first view, technology should solve the problem by itself. Its role would be to provide, in particular, energy systems with no or very low carbon emissions. While economic development would proceed in a sustainable manner, no behavioural change would be needed or implied to get this result.

Perhaps representative of this view is the recent paper by a group of US scientists reporting in Science (Hoffert et al., 2002): "Primary power consumption today is ~ 12 TW, of which 85 per cent is fossil-fuelled. Stabilisation at 550, 450 and 350 ppm CO_2 by Wigley et al. Scenarios require emission-free power by mid-century of 15, 25 and >30 TW, respectively. (…) Arguably, the most effective way to reduce CO_2 emissions with economic growth and equity is to develop revolutionary changes in the technology of energy production, distribution, storage and conversion."

The opposite view would give a less important – or even trivial – role to technical change. In this worldview, changes in behaviour would achieve a significant part of the emission reductions. People would reduce their use of carbon-intensive materials and services. They may, for example, travel less for leisure and spend leisure time and money on different and less carbon-intensive activities.

A good representative of this second vision is Jancovici (2002), although he does not dismiss a role for technology. He sees sustainable and carbon-free energy being mainly derived from nuclear and solar power (and its derivatives); he estimates that together (over the long term) these would provide about half of today's primary energy. As a consequence, in order to meet CO2 targets, per capita energy consumption in industrialised countries would need to be significantly reduced. To stabilise CO2 concentrations below 450 ppm implies that many commodities or services would be available in lesser quantities than today – in particular such highly energy-intensive commodities as mass air and road travel, inexpensive concrete-based construction for housing or out-of-season fruits.

This argument echoes that made by developing countries experts or negotiators that "luxury" consumption should not be given the same weight in analyses as people's "basic needs". It also relates to the argument of "philosophers" as noted by Grubb (1997): "*We can and should learn to become less obsessed with material consumption and the burning of carbon that goes with it, and that by putting more emphasis upon the quality of our physical and social environment we would anyway be better for it*".

An example of these two trends may help clarify the differences. Using transport, and according to the first vision, fuels would become carbon free. They would be manufactured from nuclear or renewable energy, or carbon emitted would be captured and stored at some point in the refining process. This may require deep changes in the way cars and trucks are designed and built – such as replacing current motor technology with fuel cells – and would allow people to keep their travel and commuting habits unmodified. According to the second vision, new standards for energy efficiency should be imposed on carmakers, which could modify the size and the weight of most cars. Moreover, use of cars should be regulated, either by higher fuel prices or by restrictions for use in cities, or both; more efficient mass transit systems should be given priority in land-use and public investments, so as to encourage people to switch transport modes. Even more, people should be induced to reduce travel – both in terms of distance and frequency, through pricing or other policies. Urban planning and related policies (such as, for example, credit policies for construction work) would tend to maintain or increase density in urbanised arenas, not expand them.

3.3.2 Fuzzy limits

Although this debate might be rooted in differing political philosophies and differing views on the role of governments, the distinction between behavioural and technical changes in not as clear-cut as the discussion above might suggest.

For example, the choice of riding a bicycle rather than driving a car or taking public transport for short distances may be thought of as purely behavioural, and individually determined. But this choice may also stem from a determination of the relative safety of the two choices – which itself depends on the building of bicycle paths. The case for using a mass-transit system may be affected by parameters such as its proximity, frequency, comfort, safety, and cost. Eventual determinants might be the numerous factors that determine the density of cities and suburbs – from consumer choices to policies by local authorities, credit facilities and the like.

In some cases technical and behavioural components are even more closely linked. To choose to buy a "hybrid" car, twice as efficient because it associates a small thermal engine with an electric one, currently implies accepting that driving faster than certain speeds is only possible for short periods. Even more generally, technical change requires a succession of steps, from invention or innovation to dissemination, that require human intervention: there is always a behavioural component in it that policy instruments must take into account to be effective.

Another example might help illustrate this point. Bus systems might be instrumental in paving the way toward cleaner fuels and motors. As pointed out in a recent IEA study (IEA, 2002d), "*For many alternative fuels, infrastructure is undeveloped and unfamiliar to consumers. This will be less a problem for* [public] *transit vehicles since they are centrally fuelled by staff that can be trained to maintain vehicles properly and handle fuel safely*". However, to be able to accomplish this, bus systems must first become more efficient. More rapid bus systems, protected from gridlock of other vehicles, become more attractive. They carry (faster) more passengers that could pay (justifiably) higher fares. This makes bus companies wealthier, enabling them to eventually buy new, more modern buses, and perhaps move up the technological ladder towards cleaner fuels and motors.

One interesting point here is that the changes that would allow a number of commuters to switch to bus systems will save more fuel and reduce air pollutants and CO_2 emissions more than a fuel change or technology upgrade to the bus itself could achieve. These changes may require some small technological improvements – such as information systems, automatic priorities and modern ticketing – but would mainly rest on different kind of policy decisions – such as building bus lanes and thus restricting the public space allotted to private traffic.

Technology dissemination or transfer too must be looked at from different angles. Increasing the role played by already mature technologies may require different tools and policies than helping technologies in their infancy reduce costs while raising effectiveness, or developing entirely new technologies. As the IPCC (2001, volume 3, TS) has put it, "*In all regions, many options are available for lifestyle choices that may improve quality of life, while at the same time decreasing resource consumption and associated GHG emissions. Such choices are very much dependent on local and regional cultures and priorities. They are very closely related to technological changes, some of which can be associated with profound lifestyle changes, while others do not require such changes.*"

A related problem is the "rebound effect" – when technical changes reduce the costs of an activity, leading to increases in that particular activity. For instance, more-efficient cars might be able to travel longer distances at lower cost – but the lower cost may induce drivers to use their cars more frequently and for longer trips, offsetting some of the efficiency gains. The increase in real income derived from increases in efficiency can also be used for other activities – some of which may themselves lead to increases in emissions.

In other cases, however, the contrary might be true: if carbon free energy is delivered at a higher cost to consumers, demand will shrink. As improvements in energy efficiency and decarbonisation of energy sources and vectors could happen simultaneously, it is hard to see if demand for energy will increase or decline as a result of climate change mitigation.

3.4 Creating markets for energy technologies

A recent IEA study (IEA, 2003) elaborates further on the question of deploying market policies from 22 case studies in several IEA member countries. The case studies are analysed from three different perspectives:

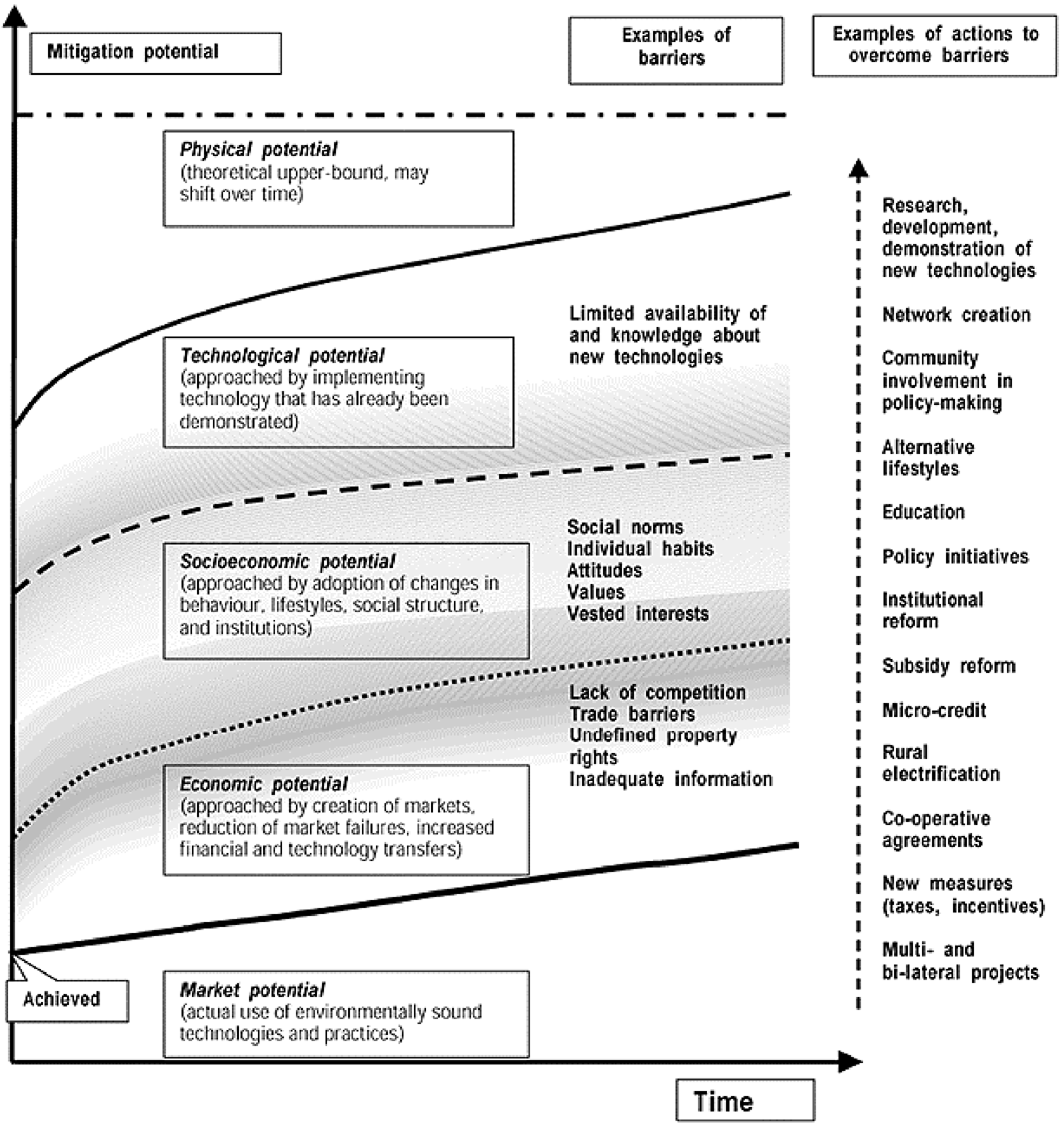
- the research, development and deployment perspective ("R, D&D"), that builds on the learning-by-doing process to demonstrate that government can play a valuable role with policies that support initial deployment of new technologies;
- the market barrier perspective, that focuses on the barriers that slow the adoption of new technologies by markets and the role government might play to reduce these barriers (economic analysis is central in this perspective); and
- the market transformation perspective, which offers a broader set of practical considerations in relation to behaviour and roles of market actors, and ways to influence them.

The relative importance given to the three perspectives differs in each of the cases studied. Obviously, ready-for-use and commercially mature end-use technologies do not require the same mix of policies that most renewable energy technologies do today. Nevertheless, one key message developed in this study is that policy initiatives designed to facilitate the adoption of cleaner energy technologies are unlikely to succeed unless policy designers pay attention to each of these three perspectives. It is necessary to:

- Invest in niche markets and learning in order to improve technology cost and performance;
- Remove or reduce barriers to market development that are based on instances of market failure – the most important being the lack of "internalisation" of market externalities such as pollution and GHG emissions;
- Use market transformation techniques that address stakeholders' concerns in adopting new technologies and help to overcome market inertia that can unduly prolong the use of less effective technologies.

The need for a comprehensive set of actions to promote technology innovation, development and dissemination is also acknowledged in the IPCC Third Assessment Report (IPCC, 2001). Figure 2 below sets up a conceptual framework for the penetration of environmentally sound technologies. It shows how different maturation stages in the innovation process help distinguish different "potentials" for mitigation – and require different types of action to overcome various barriers.

Figure 2. Penetration of environmentally sound technologies: a conceptual framework.



Source: IPCC, TAR, Volume 3, TS

4. POLICY TOOLS

As recognised by the OECD (2001) in considering innovation and the environment, "there is no guarantee that innovations will appear when and where they are most needed, or at a price that reflects all environmental and social externalities associated with their deployment. Governments need to create a policy environment that provides the right signals to innovators and users of technology processes, both domestically and internationally; to fund basic research; and to support private initiatives in an appropriate manner."

This section considers what policy tools governments could – or even should – use to facilitate or speed technical change. Some are specifically oriented towards innovation – like financing research and development. Others might be oriented towards technical change through dissemination of existing technologies; they could aim at reducing CO_2 emissions (or fulfilling other purposes of energy policies), or at inducing technology improvements from "learning-by-doing". Other policy tools are less specific: they deal directly with emissions. Nevertheless, they are likely to have (and might be more specifically shaped so as to have) indirect effects on technical change and innovation.

4.1 Subsidising R&D

Research and development subsidies are a traditional area for government policies. Results from R&D efforts have many characteristics of public good – in particular when investing companies face difficulties in ensuring excludability due to spillover effects. As such, markets often undersupply them. This is all the more true at early stages of technological development, when success is uncertain.

Innovation theory suggests that spillover is the main reason for under-investment in research and development efforts by private firms. However, international spillovers are starting to be seen as a potentially positive feedback for R&D on environmental control technologies. For example, renewable energy technologies that are competitive in the markets of the OECD economies may also have large global benefits, allowing low-cost emissions reductions in developing countries (Clarke & Weyant, 2003).

Despite the recent private-sector support for "social responsibility" and "sustainability" reporting, and the acknowledgement by many major private-sector players that "clean" technologies will form one of the important markets of tomorrow, private-sector R, D&D. efforts, although increasing, have been relatively limited (IEA, 2002g). Conversely, government funding of R, D&D, while reduced below levels of the 1980s, is a often chosen as a key element in national GHG mitigation policy – and is especially frequent in North America where such measures represent close to a quarter of newly implemented policies (IEA, 2002g).

In analysing innovation in relation to environmental policies, the OECD (2001) suggests that government should "support long term basic research through funding and efforts to build capacities… and applied research activities when they are clearly in the public interest (e.g. protection of public health and environment) and unlikely to be provided by the private sector by:

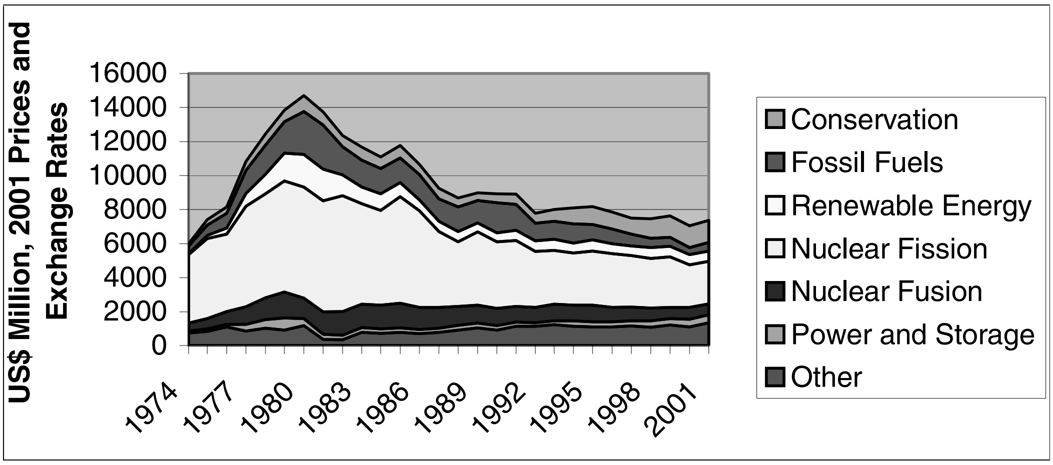
- Co-operating with the private sector to develop and diffuse new technologies.
- Facilitating public-private and inter-firm collaboration with the innovators of cleaner technologies and practices.

- Seeking out opportunities for greater international collaboration on research especially on issues critical for sustainable development.

- Allowing competition among technologies that can meet the same policy objective, and equal access to “learning opportunities” (e.g., protected niche markets and similar schemes) by foreign as well as domestic investors.”

Developing advanced technologies requires not only applied research and technology refinement, but also the innovation that stems from advances in basic science. Knowledge flowing from basic research is what will feed the development of new approaches that could reduce clean technology costs. It could also lead to new, unforeseen technologies and novel approaches to providing energy services. Effective linkages between basic science and applied technology will be important to ensure that these opportunities are opened up (IEA, 2003d).

Figure 3. IEA Government Energy R&D Budgets, 1974-2001



Source: Data reported to the IEA by IEA Member countries

Current levels of energy R&D investment are unlikely to be adequate given the magnitude of the climate challenge. Energy R&D investments in IEA Member countries peaked in 1980 and declined substantially thereafter (see Figure 3). While spending on conservation is at historic levels, spending on renewable has been lower in recent years than in the period 1977 to 1986. Greater and sustained commitment is needed to energy technology R&D, to technology demonstration, to the underlying basic sciences and to market uptake of new technologies, in order to ensure that low-carbon and low-cost technologies are available when needed.

4.2 Technology and performance standards

There are situations where technology and performance standards could prove an effective tool to disseminate effective and environmentally friendly technologies. For example, a recent IEA study looking at the energy consumption of appliances provides clear evidence that standards can address one area of market failure (IEA, 2003c). This case seems to be a textbook application of market failure theory. Most households and small business do not care much about electricity costs – and those who do may not have the correct information on how to make savings – or the resources to make even the small up-front investments required.

The conclusion of this work suggests that residential appliance and equipment policies should be strengthened to target the least life-cycle cost for each appliance class. This would allow cost-effectively improving the energy efficiency of residential appliances. In the case where such policies might be applied in IEA member countries, such policies might save as much as 322 MtCO2 per year by 2010 – equivalent to taking over 100 million cars off roads in IEA countries. Setting such standards at a more stringent levels – for example if they also accounted for the additional value of externalities such as reducing climate change and local environmental damages – would lead to greater benefits.

A softer kind of standard may be provided when the mandate is to give information to consumers rather than set limits on manufacturing. These often take the form of labels. Labels directly address the market failure arising from the lack of information of end-use consumers. They have already proven effective in most Member countries for appliances, sweeping the least efficient ones out of markets (IEA, 2003c).

While technology and performance standards may prove invaluable in promoting efficient end-use technologies at the end-user level, their application is much more controversial from the industry perspective. Such concerns arise from clear economic principles: standards are usually considered more costly than market-based solutions. There are two reasons for this: (1) regulators cannot accurately know the abatement cost curves of all industries (which have little interest in letting them know – even when such curves are known by the industries themselves); and (2) even if costs are known, implementing efficient reductions risks being perceived as unfair and faces strong opposition. As a result, command-and-control regulations tend to force firms to take on similar shares of the pollution-control burden, regardless of the costs.

Another objection to standards is that they are often set at a more stringent level for new plants than for existing plants. While such differentiation seems legitimate – it is sometimes much costlier to adapt old plants than new plants to new standards – one possible perverse effect is to raise the costs of new plants and drive companies to prolong the lifetime of older, sometimes much more polluting installations.

One solution to these objections is to seek to create markets through performance-based standards. The output-based option in the current tradable permit scheme in the UK or the dynamic target option suggested for countries (Baumert *et al*., 1999; Philibert & Pershing, 2000) are representative of tradable performance obligations. Such tradable performance standards combine the efficiency properties of market-based instruments with the technology focus of performance standards; such approaches are particularly appropriate when reducing the output is not an option for achieving the target.

Mandatory technology requirements could help eliminate the least efficient technologies from markets and promote the more efficient ones that are already available. However, they are usually ill-suited to stimulating technical innovation, as they do not give any incentive to the development of even more efficient technologies. This is reflected, for example, in the ranking of instruments for environmental protection in OECD (2001): (Governments should) "*provide permanent incentives to innovate and diffuse technologies that support sustainable development objectives, by expanding the use of market- based approaches in environmental policy. When market-based instruments are not appropriate, use performance standards in preference to measures that prescribe and support specific technologies.*"

Performance standards can be of different types. The European Union traditionally tends to base required performance standards on either the "best available technologies" (BAT) or "the best available technologies not entailing excessive costs" (BATNEEC). While such performance standards again could be efficient means for disseminating best available technologies, they provide little incentive for further technological improvements. As Jaffe *et al*. (2002) outline, under such approaches "*a business that adopts a new method of pollution abatement may be 'rewarded' by being held to a higher standard of* *performance and thereby not benefit financially from its investment, except to the extent that its competitors have even more difficulty reaching the new standard."*

In other Member countries, notably the U.S., governments or local authorities sometimes set more ambitious targets than can be met through existing technologies, with the aim of "forcing" technology developments (an approach that has been suggested for dealing with climate change). However, while this approach has proven effective in some cases, in others it has not, for example the "zero emission vehicle" percentage set in California. The standard proved too demanding for the auto manufacturers to meet – and the dates have been rolled back several times. However, the California standard has clearly promoted the use of hybrids, and the global auto manufacturing effort to reduce emissions has been in large part driven by California laws.

The difficulty in setting over-ambitious standards is that regulators do not know the exact amount of improvement that is feasible; standards thus run the risk of being either unambitious or of being ultimately unachievable. To make things worse, companies often anticipate that political authorities will waive the target if technological improvements are insufficient, particularly if the consequences of a full enforcement would be very costly and/or politically difficult.

The dynamics of incentives for innovation is unclear in such a case. Companies subject (even indirectly) to regulation might prefer not to develop new technologies – and instead wait for authorities to waive the regulatory target. While regulations provide a strong incentive for innovators, in many industries (for example, the automobile industry), the level of technical and financial resources needed to develop radically new technologies and more generally the entry barriers are too high for outsiders.

In sum, there are areas – such as the case of appliances in the household and small business sectors – where standards might be efficient and cost-effective, and areas –such as industry and power sectors – where they risk being less or not efficient at all, and less or much less cost-effective.

4.3 Subsidising dissemination

A large number of approaches have been taken to subsidise technology developments, from earmarked taxes to straightforward government (or government-run specialised agency) subsidies, to tax exemptions to other fiscal arrangements (e.g., allowing accelerated depreciation of clean investments). However, given public fiscal limitations, governments are increasingly seeking to have consumers rather than taxpayers subsidise renewable energy technology developments.

However, governments continue to provide direct subsidies to technology. Ongoing policies are a reaction – given the need to take action – to the difficulty in setting up market-based instruments such as taxes or a cap-and-trade system. While subsidies are a "second-best" instrument, they are politically acceptable. It has also been argued that some technologies require further "learning" investments to become competitive in markets – even if all externalities were fully incorporated into the price. Governments, have a long-term interest in promoting more efficient technologies – in the case of climate change, carbon-free or carbon-lean technologies – and ensuring they will be available in the future at acceptable price. One way of ensuring this is to bring such technologies further down their learning curve; one tool for doing so is to subsidise them.

However, making the choices on which technology to promote is not an easy task. Jacoby (1998) states that "picking winners is a difficult art, and spending money effectively is a daunting challenge in the midst of regional and industrial demands for a share of the pie." He notes that the expertise in many technical areas resides in private industries – particularly oil, chemicals and electric power. "Government-industry partnerships and tax subsidies can help direct their efforts, and useful experiments are now being tried. But the only way to truly attract industry attention is through an influence on the bottom line, which necessarily involves (among other things) price expectations. In the energy sector at least, large-scale technical change with no price incentive is a non sequitur."

Various instruments have been used to support renewable energy technology dissemination, including: bidding processes (Ireland, France and UK); fixed feed-in tariffs (US in the 80s, Germany, Spain, Denmark, France, India); tradable green certificates schemes (Italy, Belgium, UK). The first might be characterised as "quantity" instruments, the second as "price" instruments, and the third as "quantity with flexibility" instruments.

Price instruments that do not allow controlling quantity but allow controlling marginal cost have proven, somewhat paradoxically, to offer less control on total costs than quantity mechanisms (Ménanteau *et al*., 2001). Guaranteed prices have proven more effective in fostering deployment: within the EU more than 80% of added wind power capacities in 2000 were in the countries with guaranteed prices, notably Denmark, Germany and Spain (Lamy *et al*., 2002). UK and France have given up the bidding processes, replaced by fixed feed-in tariffs in September 2001 (France) and a green certificates scheme in April 2002 (UK). India also moved from investment incentives to feed-in tariffs (Philibert, 2001). Feed-in tariffs may easily be differentiated amongst technologies if the political intent is to promote various technologies at different stages of maturity.

However, the value of fixed feed-in tariffs has been questioned: it raises costs to electricity consumers, and may not provide any significant incentive for innovation. Diversified tariffs, decreasing both with site productivity and over time, may help provide continuous incentives to technical improvements. A balance must be found, however, between providing this incentive by progressively reducing the extra cost paid as a learning investment and the risk of suppressing the minimum long-term security needed by developers.

Green certificates are thought to provide some advantage in stimulating competition, and particularly relevant in more deregulated markets. However, unless certificates are granted preferentially to certain technologies, this policy tool may serve less well. This is particularly true if all technologies are in competition and if the political intent is to promote various technologies at different stages of maturity. Moreover, the need for developers to get bank loans and for distributors to hedge against certificate price volatility may privilege long-term contracts and shrink green certificate market size.

Procurement programmes also allow governments to promote the dissemination of efficient, clean technologies. The scale of government purchasing give producers confidence in the depth of the markets, ultimately allowing them to proceed with production, and reap the advantages of both experience and economies of scale.

4.4 Taxes and cap-and-trade systems

Pigouvian taxes and cap-and-trade systems are not specifically designed to foster technical change but they do have innovation effects: both systems modify the price of using the commodity that creates the externality. As noted by Hicks (1932, 1963), "*A change in the relative prices of the factors of production is itself a spur to invention and to inventions of a particular kind – directed at economising the use of a factor which has become relatively expensive*."

Taxes and cap-and-trade systems are not necessarily equivalent in fostering innovation, as attested to by a growing body of economic literature. A recent review by Jaffe *et al*. (2002) suggests that both auctioned and freely-allocated permits are inferior in their diffusion incentives to emission tax systems, but superior to command-and-control instruments. Under tradable permits, technology diffusion lowers the equilibrium permit price, thereby reducing the incentive for participating firms to adapt. Milliman and Prince (1989) estimated that incentives for innovation were greater under an emission tax than under free emission permits, and higher still under auctioned emission permits. However, an unambiguous exhaustive ranking of instruments may not be possible on the basis of theory alone.

Other studies (e.g., Parry *et al*., 2002; Requate & Unold, 2003) suggest that the welfare-based ranking of various instruments is only partially dependent on their effects in fostering technical change. In the presence of cost-diminishing innovation, firms and regulators may have the same interest in reducing tax levels, while they have opposite interests in modifying the amount of permits.

Generally speaking, cap-and-trade systems and Pigouvian taxes offer important advantages over more focussed policy tools. They are economically efficient by equalising marginal cost of reduction all over the board. They tend to foster technical improvements by “pulling the demand”, influencing *a priori* all behavioural elements in the technical change chain. Of course, taxes and cap-and-trade systems do not distinguish between the value of technical change versus behavioural change.

The efficacy of all market-based instruments, however, can be questioned from the viewpoint of “market failures”. Although they themselves are intended to correct an important market failure, that of “externality” issues such as pollution, they are efficient if markets are efficient – and there are many other market barriers that may need to be overcome. Insufficient or incorrect information (for example, consumers do not perceive how costly it is to own a power-guzzling air conditioner) represent a vast category of market barriers that can be dealt with through standards or labels, as discussed above.

However, from a technology development perspective, perhaps the most important “market failure” is that created by the short-term vision of most economic agents. Even if agents and firms might anticipate future allowances to be further restricted under cap-and-trade systems, or future tax levels to increase, they might not engage in the extent of near-term technology development that would be required to allow deep reductions when they will be needed. This problem is one of timing – and inherently leads the market to invest in technologies that meet near-term goals rather than discounted, longer-term objectives.

Thus, for example, actions in some sectors characterised by very long lifetime of infrastructures – such as buildings, or transport – might be too costly to implement; most of the benefits are only likely to materialise after agreed near-term caps are in place – say, after 2012. Similarly, the research, development and demonstration efforts needed to make some renewable energy technologies or other greenhouse gas mitigating options competitive in the long term may be too costly given their likely limited payback in the short term. This provides a compelling argument for policies and measures to complement those that exclusively seek to modify market prices.

4.5 Voluntary agreements

Almost every AIXG country has adopted a voluntary approach of one sort or another. Approaches vary from voluntary non-binding agreements on reporting emissions and progress to self-defined targets to negotiated agreements that are legally binding, have benchmarking and performance assessment and contain sanctions in the case of non-compliance (Bygrave & Ellis, 2002).

There is limited evidence as to the environmental effectiveness of voluntary agreements, which seem to provide little incentive to innovate and can be weakened by a lack of credibility, especially vis-à-vis public opinion. Yet voluntary agreements are likely to generate significant “soft effects” in terms of dissemination of information and awareness raising. On the other hand, their ability to reduce administrative costs remains an open question; transaction costs should also be evaluated. Finally, free-riding and regulatory capture can seriously affect the effectiveness of voluntary agreements. Available evidence on the performance of voluntary agreements suggests two main ways of using negotiated agreements and voluntary programmes efficiently: using them in a policy mix; and using them to explore new policy areas (OECD, 1999).

Voluntary approaches are seldom used as "stand-alone" instruments. Instead, they are often used in policy packages with one or several other instruments such as command-and-control regulations, tradable permit schemes, taxes or others. On-going OECD analysis based on several case studies (OECD, 2002a) notes that the great diversity of approaches makes it difficult to draw general conclusions. However, the use of voluntary approaches in combination with command-and-control policies seems to enhance technology diffusion by comparison with command-and-control regulations used in isolation, thanks to various information campaigns and forums of participants.

Combination of voluntary agreements with taxes usually means that companies accepting agreements and undertaking emission reductions are partially or totally exempted from the tax. While adding the voluntary option to the tax gives the affected companies more financial resources to undertake research and development, it may also reduce the incentive to actually achieve technology improvements (OECD, 2002a): *"When the 'shadow price' on marginal emissions approaches zero, the firm has little incentive to find ways to reduce them. Over the longer term, this could have important environmental repercussions"*.

4.6 Policy mixes

What is true for voluntary agreements may be true as well for other instruments: none is likely to be fully effective in isolation. Price mechanisms only work to the extent that markets are efficient, they do not resolve market failures. Conversely, regulatory measures are better at dealing with market failures than in directly addressing emission reductions. All IEA member countries use a broad range of policies and measures to deal with their GHG emissions, in a variety of country-dependant policy mixes (IEA, 2002g). The success of these combined approaches can only be judged in context, and there is probably no single, one-fits-all silver bullet.

5. THE INTERNATIONAL DIMENSION

While the discussion above has examined how domestic policy may be used to promote the development and dissemination of technology, it has been a hotly debated issue as to whether – and if so how – international collaboration may facilitate the process. This section examines these issues, considering both the question of collaboration amongst countries, and then the broad question of international spillovers resulting from action undertaken by countries. Finally, current and possible future policy efforts in this field are investigated.

5.1 International collaboration

Low- or no-carbon emitting energy technologies have many characteristics of a public good – especially when the carbon externality is not reflected in prices. They are thus likely to be provided in greater quantity through international collaboration. For the same reasons that justify government financing of research and development efforts, international co-operation in this field may generate important benefits.

Within a global agreement, countries are likely to provide more subsidies than they would in isolation: basic research and development, with relatively long payback periods (although high benefits) can best be supplied co-operatively. Essentially, the rationale for such co-operation is the same as for public spending in this area: as innovation is difficult to protect from spillover to competitors, there is little incentive for first movers. Thus, to promote action and limit free-riding, a co-operative approach makes sense.

In some cases, international collaboration and cost sharing seems to be a prerequisite for risky and/or expensive investments into radically new technologies. An example might be that of the ITER experiment – a step towards the development of fusion energy. Cost-sharing might also take a different form: that of sharing the learning investments necessary to reduce costs of new energy technologies and allow them to penetrate the marketplace.

In many other cases, international collaboration simply avoids duplication of efforts and facilitates information exchanges. Such co-operative ventures are provided by the IEA's "implementing agreements" (IAs) – more than 40 international collaborative energy research, development and demonstration projects. Gathering various sets of Member and non-Member countries, 15 IAs cover the energy end-use technologies, 9 IAs cover the renewable energy technologies (including one IA on hydrogen), 8 IAs cover the nuclear fusion technologies, 5 IAs cover the fossil fuels technologies (including clean coal and CO_2 capture and storage) and 4 IAs are devoted to the dissemination of information. [5]

There is little doubt that more could be done in this respect. New international agreements focusing on climate backstop technologies could, *inter alia*, aim at linking together existing technology promotion efforts – for example, those introduced by the G8 strategy to promote renewable energy sources, and the still embryonic technology transfer mechanisms under the Climate Convention (see below). Such links might provide a more organised and aggressive strategy to speed up the development and dissemination of these technologies than that offered by independent national efforts. The focus of such an effort would be on accelerating the "learning-by-doing" process that might bring technologies more rapidly into the markets.

[5] See the IEA website: www.iea.org and more specifically www.iea.org/techno/index.htm. See also IEA, 2002f for a status report. See also IEA, 1999 for a sampling of success stories.

A proposal for all countries to commit themselves to reach some agreed percentage of renewable energy sources in their primary energy supply was partly intended to accelerate learning by doing from accelerated deployment. It was supported at the recent World Summit on Sustainable Development by the EU and some developing countries, but opposed by other Member countries and most developing countries. Those opposing the agreement expressed concerns about a “one size fits all” approach and called for a flexible approach to increasing the use of renewable energy. In addition, developing countries suggested that any agreement exclusively focused on renewable energy would divert attention away from their primary goal of ensuring universal access to energy services for the poor. As a consequence of this opposition, the Summit did not establish any formal commitments.

A number of recent proposals have been made for technology-based international agreements as successors to the Kyoto Protocol. Scott Barrett (2001) suggests the negotiation of a new agreement focusing on R&D funding. While such an agreement might complement the current Kyoto Protocol, Barrett maintains that over time it could fully replace it. Under his proposal, base-level contributions would be determined on the basis of both ability and willingness to pay, and could be set according to the United Nations scale of assessments. To provide incentives for participation, each country’s contribution to the collaborative effort would be contingent on the total level of participation. The research emphasis would be on electric power and transportation. This would be a “push” programme for R&D – a dimension absent from the Kyoto approach.

However, Barrett also proposes a complementary “pull” incentive to encourage compliance and participation. He suggests that the most attractive approach would be to agree on common standards for technologies identified by the collective R&D effort, and established in complementary protocols. As examples, energy efficiency standards could be established for automobiles, requiring the use of new hybrid engines or fuel cells, or standards for fossil fuel fired power plants might require capture and storage.

A standards-based approach was also advocated by Edmonds (1999, 2002) and Edmonds & Wise (1999). Under their hypothetical protocol, any new fossil fuel electric power plant and any new synthetic fuels plant installed in industrialised countries after 2020 would be required to capture and dispose of any carbon dioxide from its exhaust stream or conversion processes. Developing countries would undertake the same obligations when their per capita income equals the average for industrialised countries in 2020 in purchasing power parity terms.

The most problematic aspect of such a strategy might be one of credibility – a problem inherent in approaches based on still-to-be-developed technologies (see discussion above). No less important is the cost issue. Edmonds & Wise themselves recognise that the cost of achieving a given concentration level with such a protocol would be 30 per cent higher than the economically efficient cases of taxes or tradable permits. This estimate may even be too low, as the structure of the agreement would not encourage some of the most cost-effective energy efficiency improvements. In addition, the politics of some technology proposals may make them difficult to implement – particularly if they tend to disadvantage specific – and politically powerful – segments of the economy. Thus, for example a technology proposal that calls for phasing out coal may meet the same experience as faced in England or Germany where closing down even money-losing coal mining operations is a process that takes decades.

5.2 International spillovers

International spillover comprises many complex processes including substitution due to price effects, diffusion of technology innovations, and policy and political effects.

One important effect is that, in the course of industrialisation, newcomers tend to see their energy intensity peak at lower levels than countries having been industrialised earlier (Martin, 1988). This is modelled by Grubb *et al*. (2002), who consider spillover effects from the Kyoto protocol in terms of their aggregate impact on emission intensities over this century. In model results with no international spillover, limiting industrialised country emissions alone has limited environmental benefit; in the base case atmospheric concentrations by the end of the century rise to 730 ppm. However, this implies a large divergence of emission intensities, contrary to both empirical long term aggregate trends and to the continued convergence expected with economic globalisation. In contrast, if spillover leads to convergence of emission intensities by 2100, atmospheric concentrations are kept to below 560 ppm and are close to stabilising.

This result may seem very optimistic. However, although the aggregate degree of spillover is uncertain, the available evidence suggests that it will be important and environmentally beneficial in aggregate. Spillover will help to spread the global effectiveness of the Kyoto first period and subsequent commitments, and deserves much further scrutiny. Positive spillover effects might be greatly enhanced through technology transfer policies – and/or mechanisms such as the clean development mechanism or emission trading with developing countries.

While international spillovers occur spontaneously, they may also be accelerated by two different sets of policies. Policies aiming at facilitating international trade and investment, even without any climate focus, might have a positive side effect in fostering technical change, notably in developing countries. Other policies may be shaped precisely to speed these climate friendly changes; they are considered below.

5.3 Technology transfer policies

Over the past few decades, an important policy tool to promote the spread of technology to the developing world has been financial assistance – either through grants or through preferential or concessional loans. More specific to climate change are the Climate Technology Initiative and the Global Environment Facility. Since its inception, the GEF has given $1 billion for climate change projects and leveraged more than $5 billion in co-financing. Usually, GEF funds are linked to other loans from multilateral institutions (e.g, the IBRD or the ADB); they are also linked to projects financed with national or bilateral funds. More than half has been devoted to renewable energy projects in 47 developing and transitional countries.

Of particular interest is perhaps the GEF operating programme n°7, built around the notion of learning-by-doing. One of its objectives is the reduction of the costs of low greenhouse gas emitting technologies by increasing their market shares. The program considers several backstop technologies for both supply and demand sides, although it emphasises:

- Photovoltaics for grid-connected bulk power and distributed power (grid reinforcement and loss reduction) applications;
- Advanced biomass power through biomass gasification and gas turbines;
- Advanced biomass feedstock to liquid fuels conversion processes;
- Solar thermal-electric technologies in high insulation regions, initially emphasising the proven parabolic trough variant for electric power generation;
- Wind power for large-scale grid-connected applications;

- Fuel cells, initially for mass transportation and distributed combined heat and power applications; and

- Advanced fossil fuel gasification and power generation technologies, initially to include integrated coal gasification/combined cycle technologies.

It is noteworthy that through the GEF, developed countries are funding learning investments in advanced clean technologies in developing countries only – and no such collaboration exists between OECD countries. This suggests a possible policy focus.

The Marrakech Accords created a Special Climate Change Fund under the Convention to provide additional assistance for adaptation, technology transfer, energy, transport, industry, agriculture, forestry, and waste management, and broad-based economic diversification. However, as the fund was created in a context of declining funding of official development assistance (ODA) and, more generally, in a context of increasing scarcity of public spending in most OECD countries, many observers believe that while it will help to finance capacity building at national levels, it will never be large enough to finance the costs associated with the profound changes in the energy sector required to promote development while reducing global emissions.

Concerns about the adequacy of funding, an interest in lower-cost opportunities for Annex I emissions reductions, and an interest in engaging non-Annex I Parties in actions to mitigate climate change all contributed to the creation of the Clean Development Mechanism, one of the most innovative features of the Kyoto Protocol. While the GEF and other Funds rest on public financing, the CDM is intended to facilitate the financing of emissions reductions in developing countries and technology transfer from the private sector. In the context of this paper, the issue is whether the CDM wil promote the development and diffusion of technology.

To make such an assessment, it is necessary to consider whether the CDM will work and at what scale – and whether this will be adequate to influence technology trends. The jury is still out on how effectively the CDM will work. Proposals to restrict the number of projects accepted (through legitimate fears that some projects might not actually contribute to “real” reductions) are frequently made by Parties. Ultimately, if too few projects are allowed through, the net environmental benefits will be lower – even if each individual project is environmentally better. If, on the other hand, too many of these projects “would have happened anyway”, not only will the global level of emissions increase above agreed levels (Bernow *et al*., 2001) but, perhaps more importantly, truly additional projects that would expand niche markets for new technologies may be crowded out.

Information from economic models does provide some context for assessing the environmental and financial potential of the CDM regime. In simple terms, CDM can be modelled as emissions trading with some transactions costs. Thus, models that examine the benefits of global trading can provide some estimate of both the volume of CO_2 reductions that would be generated through projects, and the financial revenues such projects would generate for clean technology.

Model results of a “perfect” CDM system suggest annual revenues of about $10 billion/year (presuming US participation). While this represents only about 10 per cent of current foreign direct investment in the developing world, it is likely that a significant share of the investment would be in the energy sector – and could certainly influence the types of technology choices made.

Unfortunately, while total investments may be large, the CDM value of most projects would be relatively small. Some of the most innovative projects may need more than a small carbon price adder to make them commercial – so CDM by itself may not promote market penetration of expensive options without other price supports. These considerations partly explain the decisions at Bonn and Marrakech to develop simplified rules for small-scale projects, notably in the fields of energy efficiency and renewable energy sources. Small projects can hardly afford transaction costs and would benefit from simplified procedures, while any environmental risks in promoting such projects would be minimal.

Another quite different approach to the CDM process has yet to be legally tested in the political arena of the UNFCCC. Under this interpretation, policies may be defined as CDM projects – and governments could get CDM credit for adopting them as long as the results could be quantified, and additionality was verifiable. An example of such a programme might be an effort by a city to put in new bus lanes, or set renewable energy targets. If the GHG reductions from these plans could be assessed, the credits they generate could be offered on the international market. In such a case, the CDM process would have characteristics more closely related to the emissions trading regime – and could bring significant benefits both in terms of technology development

Another means for accelerating technology transfer to developing countries would be their participation in a global emissions trading framework, possibly under options such as non-binding and/or dynamic targets, which may make integration into global emissions trading regime more palatable to them (Philibert & Pershing, 2000; IEA, 2002a). Under such a regime, as under the clean development mechanism, entities from industrialised countries (governments or companies) would likely pay for the incremental costs resulting from technology improvements incorporated in new investments.

6. CONCLUSIONS

Based on the discussions above, a number of general conclusions can be drawn. These are related both to issues affecting the timing of policies, and to the appropriateness of policy mixes in promoting new technology development. Each is discussed in turn below.

Wigley *et al*. (1996) introduced the concept of optimal pathways towards predefined concentration levels. They concluded that deferring the bulk of abatement efforts would be a cost-effective approach, arguing that sunk investments, technological change, discounting, and natural decay of atmospheric CO_2 would contribute to making later reductions less expensive that earlier ones.

A number of arguments were made that would modify their initial conclusions, ranging from the possibility that future climate change "surprises" requires meeting lower concentration levels than previously anticipated (Ha-Duong *et al*., 1997) to the role of endogenous technical change (Grubb, 1997). Furthermore, while Wigley's model supposed exogenous technical improvements, the role of learning by doing processes implies a more complex picture. Learning investments may well be necessary in the near term to make future reductions cheaper.

Nakićenović (2002) took the opposite view, arguing that, in conjunction with RD&D, timely investment in new technologies with lower CO_2 emissions might be a more cost-effective strategy for reducing global emissions than postponing investment decisions in the hope that mitigation technologies might somehow become more attractive through "autonomous" RD&D improvements and cost reductions in step with natural turnover of capital: *"Postponing investment decisions will not by itself bring about the technological change required to reduce CO_2 emissions in a cost-effective way. Even worse, under unfavourable conditions it might bring about further "lock-in" of energy systems and economic activities along fossil-intensive development paths"*

Such investments may occur through "dissemination subsidies" that may not necessitate more comprehensive policies to directly or indirectly modify the price system.. As Roehrl and Riahi (2000) put it, "*scenarios of accelerated technological change might require long-term R, D&D commitment in new energy technologies, up-front investments and accumulation of experience in niche markets. This requires both long-term perspectives as well as long-term policy orientations rather than a focus on short-term emission reduction targets.*"

However, the broader role of modifying behaviour as a key component of technical change – cannot be neglected, nor the fact that technical improvements tend to accumulate over time. Following this "path dependence" argument, early bifurcation towards lower carbon emitting technologies would bring costs down while further accumulation of technical progress on carbon intensive paths would further lock-in our societies into high carbon future.

The problem of timing has another dimension – that related to the difficulty of negotiating technology agreements. According to the IPCC, the main near-term alternative for abatement is energy savings – and "hundreds of technologies" in all areas, are required to provide these savings. Launching separate technology agreements in each of these areas would be a daunting and probably unsuccessful process. Other policy tools – notably quantitative targets at country levels giving birth to domestic cap-and-trade systems and/or carbon taxes – are more likely to exploit these opportunities.

However, in the long run, if CO_2 emissions are to be essentially eliminated, non-carbon energy sources will have to power the economy. As the review of the technology options in the Appendix suggests, alternatives exist that could provide for such a low-carbon future. Technology push and pull strategies will be key in bringing these from the drawing board to practical implementation. In the short term, however, it seems clear that new, carbon-free technologies are not yet mature enough to be commercially competitive. Thus, while aggressive efforts to promote technology change are justified, they will not, alone, yield the near-term reductions critical to assure that emissions do not rise too fast in the early years. Both technical and behavioural changes must be made together.

Given the very slow capital stock turnover in many sectors, price incentives provided by these instruments – unless unrealistically high – would provide little change or promote much development of new technology.

There are some quantitative modelling results that support this analysis, in particular, a growing body of work undertaken to introduce induced technological change in climate models. By comparison with models with no technical change, that is, where current technologies only are considered, they tend to exhibit higher potential for reducing emissions at lower costs. By comparison with models with exogenous technical change, they tend to refute the view that the bulk of efforts to mitigate climate change should be pushed towards the future because abatement costs will be lower the longer we wait.

Modelling induced technological innovation faces, however, a number of difficulties arising from uncertainties. As Clarke and Weyant (2003) explain, "*the fundamental concern for modelling the induced portion of technological change is, 'How will the production function respond to innovation investment (or cumulative experience)'? There is enormous uncertainty about this response and it is not just a matter of 'the right number'; the response will change over time as technologies come and go in the market.*" They suggest three aspects of uncertainty in technological change that induced technological change models need to consider. These are the uncertainty in the potential for individual technologies, the heterogeneity and discontinuity in technology development, and the major innovations. One could add to that list the difficulty of distinguishing the effects of R&D efforts from these of experience curves in inducing technical change.

Finally, the assessment of international spillover remains in its infancy. Apart from the pioneering work by Grubb *et al*. (2002) mentioned above (see 4.2), the literature thus far seems to have only considered the negative effects of leakage as a possible result of policies undertaken by a group of countries rather than more broadly on the consequences to emission-reducing technology development. In sum, much work will be needed on modelling induced technical change and spillover effects before robust quantitative assessments of various mitigation strategies become available.

While the near-term potential for a narrowly focused technology agreement does not seem to provide a full “solution” to the climate problem, the same may not be true over the longer term. Ultimately, solving the problem will require huge reductions in emissions – essentially decarbonising the world’s energy system. Current technologies are not available to do this on the scale required. Options such as large-scale capture and storage or enormous reductions in costs and increases in capacity of nuclear or renewable energy would be needed to meet this goal. Massive R, D&D investments would seem to be critical over the longer term – and inasmuch as these can be enhanced through international co-operation, agreements may indeed provide the critical missing element to a successful next step. As shown by the current policies than support renewable energy technologies (notably in the EU, but also, for example, in India), such investments may not necessarily rest on government subsidies.

Even market transforming (taxes or caps) policies may not provide enough stimuli for the long-term future. Myopia of market actors and free-rider effects in appropriation of knowledge give too little incentive for innovation compared to what will be required in the distant future. The adoption of more comprehensive and aggressive international agreements to promote a handful of backstop energy technologies world-wide with large long term potential would add a “push” to the research and development of these technologies.

On the other hand, an exclusively “technology” focused approach is unlikely to fully substitute for a more comprehensive agreement and action portfolio. This is partly because technology improvements do not necessarily result from focused efforts, but more broadly from a whole context that includes a wide number of policies – the most important being perhaps market transformation through internalisation of externalities. However, it is also critical that we get near term results to protect the climate for reaching too high a level of concentrations. Inasmuch as technology change is slow, this implies it will be necessary to use a portfolio approach that includes both technology and other tools.

Future work will engage in a more concrete elaboration of how international co-operation on technical change could be set up, and how it could better establish or tighten links between developed and developing countries.

7. APPENDIX: KEY TECHNOLOGIES

7.1 End-use technologies

According to the IPCC (2001, vol.3 Chapter 3), sufficient technical options exist to hold annual global greenhouse gas emissions through 2010 to levels close to or even below those of 2000 -- and even lower levels are possible by 2020. For energy-related CO_2 emissions alone, the technological potential exists for reductions of between 1,350 MtC/y and 1,900 MtC/y in 2010 and of 2,950 to 4,000 MtC/y in 2020. There are, however, conflicting views as to the costs of taking such actions.

More than half of the potential comes from the aggregate effect of "hundreds of technologies and practices" for end-use energy efficiency in buildings, transport and manufacturing. Most of this potential may be tapped by 2020 with direct benefits – notably in the building and industry sectors (see IPCC 2001, Vol.3, Chapter 3).

7.1.1 The building sector

CO_2 emissions from fuels and electricity used in both residential and commercial buildings represent 98 per cent of all building-related GHG emissions. However, while developed countries have by far the largest CO_2 emissions from the building sector, energy use and related CO_2 emissions from buildings in developing countries, particularly in the Asia-Pacific region, have grown about five times faster than the global average since 1980.

By 2010, it is projected that 500 MtC CO_2 emissions from buildings could be avoided in developed countries (including EITs) at negative costs, while in developing countries more than 200 MtC CO_2 emissions could be saved at costs ranging from –US$200 to +US$50. Actions include improving building thermal integrity, reducing the carbon intensity of fuels used in buildings, and increasing the energy efficiency of appliances and equipment.

The technical and economic potential for CO_2 emission reductions in the building sector extends to more than 1 GtC by 2020 and not less than 2 GtC by 2050. However, the availability of technologies to achieve such savings cost-effectively depends on significant R&D efforts, according to the IPCC.

The built environment can revolutionise the efficiency with which it uses energy for services such as heating, lighting and cooling; can shift to renewable or non-carbon sources of energy and power; and can transform itself gradually over time via modernisation and new construction. The future buildings sector could be well integrated into a larger, integrated power and resource grid, with localised energy and environmental management systems and controls. Future buildings could be almost alive with communicating sensors, controls and microprocessors that manage energy requirements from central and distributed power systems and that allocate energy to building equipment in response to user needs. Buildings could use intelligent envelopes and components (e.g., integrated photovoltaic cells, photo-luminescent wall and floor boards, phase and adaptive materials for cladding, windows and roofs), local power systems and energy storage systems, and ultra-efficient appliances; bio- and photonic sensors and actuators; and biotechnology and other applications for water, air and waste purification.

The life cycle of raw materials for construction is another significant factor. There is a broad range of possible innovations with regard to improving the competitiveness, attractiveness and technical performances of raw materials that are local, recyclable, non-fossil and energy-efficient in their transformation and disposal processes.

Developments needed to support the emergence of such a future buildings sector include advances in materials, “smart” building components, sensors and controls, and information systems. None of these “futuristic” options for buildings, however, negate the importance of basic features such as passive solar design, optimised insulation, and efficient district heating and cooling systems – technologies that are “on the shelves” today.

7.1.2 Industry

Industry-related emissions accounted for 43 per cent of carbon released in 1995. Global industry emissions are slowly growing, while developed country industry emissions are slowly decreasing. As in the building sector, hundreds of sector-specific technologies combine to offer considerable scope for lowering CO_2 and other GHG emissions. The IPCC estimates the potential at 300-500 MtC in 2010 and 700-900 MtC in 2020 – of which a majority can be realised at net negative cost. Material efficiency improvements (including recycling, better product design and material substitution) could provide an additional 600 MtC emission reductions in 2020.

In general, Japan, South Korea and Western European countries have more energy efficient industries than developing countries, economies in transition and other OECD countries (notably the US and Australia). The latter offer the highest technical potential for energy efficiency improvements in the industry sector, though differences in economic potential may be smaller given the lower energy prices that often occur in the less efficient countries (IPCC, 2001, Vol.3). IEA work on energy indicators (see Unander, 2001) suggests a variety of reasons for such differences – including energy pricing, geography, and local climate.

Industries and industrial facilities of the future could adopt an increasingly integrated systems approach, that includes greater use of waste heat and plant-wide optimisation of energy sources and sinks; on-site generation of electricity with integral carbon separation and capture; and increasing process efficiency, making use of revolutionary processes as they emerge from R&D, on for example, nanotechnologies, micro-manufacturing and bio-processing. Advanced industrial processes could also rely on high-speed and high-capacity computing, robotics-using biological/computer interfaces, artificial intelligence, wireless communications, power electronics and photonics. In the long term, continued R&D could yield increasingly bio-based chemical products.

Improvements in the efficiency of existing processes can contribute to reducing greenhouse gas emissions during a transition phase. As existing infrastructure reaches the end of its useful life and depreciated capital equipment is replaced, and as new facilities are built, dramatic changes can be introduced. Ultimately, flexible industrial/energy complexes that can accept a variety of non-renewable and renewable primary fuels, and produce multi-product outputs – electricity, hydrogen, chemicals and transport fuels – could emerge. All input streams to such complexes would be used in the final products, or converted to value-added inputs for other processes or industries.

Advances in materials, separation technologies, bio-catalysis and bio-processing, sensors and controls, and nanotechnology, among other areas, are needed to underpin this clean industrial future. Fundamentally new processes for energy-intensive industries, such as steel making and pulp and paper production, are also needed.

7.1.3 Transport

IPCC analyses suggest less optimistic prospects for the transport sector, which currently contributes about 20 to 25 per cent of global CO_2 emissions. Most evaluations suggest that technical improvements could slow the growth in emissions, but not reverse it. The primary problem in the sector is its very rapid growth rate. In fact, transport emissions could be even further exacerbated by the so-called "rebound effect" possibly arising from lower travelling costs (and thus, higher volumes) following technical improvements.

The IEA World Energy Outlook (2002c) "Alternative Policy Case" considers a range of policies that could help restrain OECD transport energy demand and CO_2 emissions after 2010 -- but makes it clear that these policies would have only a limited near-term effect. It notes that effective policies are available for containing both passenger-vehicle and road-freight energy demand, although it suggests that the growth in demand for aviation fuel remains a major concern, and the increasing volume of passenger and freight-transport presents a long-term problem.

Transport systems in the latter half of this century could be dominated by vehicles, ships and aircraft with very low CO_2 emissions. This scenario could feature a mix of vehicle types – fuel-cell vehicles powered by hydrogen, electric vehicles, vehicles running on biofuels, and hydrogen-powered aircraft. The hydrogen, biofuels and electricity used in transport could be produced with near-zero well-to-wheel CO_2 emissions – this point is further considered below.

Vehicles can be much more efficient than today's vehicles, lessening the demand on future fuel and electric drive systems, as well as helping to reduce emissions substantially during a transition period. Whether vehicles are powered by hydrogen, electricity or biofuels in the future, if their demand for fuel can be cut by half or more, the job of achieving a near-zero-emission system will be much easier than otherwise. A 50% reduction in vehicle fuel use is quite possible with aggressive application of incremental and advanced technologies. Hybrid vehicles could be especially important for the substantial efficiency gains they offer and, perhaps, as a transition technology to electric drive vehicles.

Intelligent transport infrastructure and greater vehicle automation technologies could lead to much more efficient transport systems, especially for public transport.

Natural gas could play an important role in the transition to a near-zero-emission transport system. Low-emission biofuels could also play an important role, especially during the transition period to hydrogen or electrically powered vehicles.

Developments needed to support the emergence of such a transport sector include advances in fuel cells, batteries and other electricity storage media; hydrogen storage; and cellulosic ethanol production. In addition, the long process of developing the necessary infrastructure for future vehicles and fuel systems must begin soon, especially for hydrogen (IEA, 2003b).

7.2 Fuel switching

In the near term, while energy supply and conversion remains dominated by fossil fuels, switching from coal to oil or gas can play an important role in emission reduction. If energy conversion efficiencies were similar, a shift from coal to oil would imply a reduction in carbon emissions of 26 per cent, from oil to gas 23.5 per cent, and from coal to gas 43 per cent per unit of primary energy. Taking into account the estimated methane leakage in the production, transport and use of these various fuels would slightly reduce the gap between oil and gas and widen the gap between oil and coal.

When fossil fuels are used to produce electricity, the advantage of natural gas is increased by the higher efficiency of current, state-of-the-art, combined cycle gas turbine technologies over oil and coal-fired power plants (see below). IEA's World Energy Outlook (2002) foresees that the share of gas in world energy demand will increase from 23% today to 28% in 2030. New power stations will take up 60% of this increase, usually using CCGT.

Fuel switching toward natural gas seems limited more by geographic constraints than by technology considerations. Although 90 countries hold significant natural gas reserves, 70 per cent of world reserves are located in the former Soviet Union and the Middle East. The reserve/production ratio of 65 years globally is unevenly distributed, from 250 years for the Middle East to only 9 years for North America (IEA, 2001a). Even more striking is the ratio of natural gas reserves to total energy consumption, as suggested by Siddiqi (2002). This ratio is lower than three years for some large countries with huge coal reserves such as China, India and the USA. In these cases, fuel switching towards natural gas is likely to aggravate rather than resolve energy security concerns.

Technological progress, however, has proven instrumental in fostering gas use and, in particular, international gas trade, especially with liquefied natural gas (LNG). It has led in the past decades to sharp decreases in investment and operating costs all along the LNG chain. Investment costs for liquefaction plants and tankers have been more than halved since the 1970s, as well as self-consumption of the entire chain. For the vast majority of experts, the downward trend in costs of the LNG chain has not yet run its course, even though many estimate that most of the reduction process has already been accomplished. (Valais et al, 2001). Similarly, future developments of high-pressure technology and offshore pipeline technology are expected to play a major role in reducing the costs of large-scale long-distance pipeline projects.

A second limit to fuel switching toward gas would be the global availability of conventional natural gas resources. Proven reserves might provide about 60 years of consumption at current rates; total estimated resources, including undiscovered gas, represent from 170 to 200 years of supply (IEA, 2001a). Technological improvements have already reduced (and will likely continue to reduce) costs of identifying new gas reservoirs, as well as costs of drilling and production engineering, allowing the exploitation of new resources. If, however, gas were to replace all other fossil fuels, reserve and resource production ratios would come down to, respectively, 15 years and 40 years at best.

Beyond these conventional resources, additional gas resources exist in sea-floor methane gas hydrates (clathrates), which are estimated to represent twice as much energy potential than all other fossil fuels combined (including the large coal and unconventional oil resources). In the US alone, methane hydrate resource estimates are more than a hundred times larger than the resource estimates of other conventional and unconventional gas (Office of Fossil Energy, 1998). Clathrates are a crystalline form of water and mostly methane stable under pressure-temperature conditions common in shallow marine sediments and permafrost. They can also be used for energy storage and transportation, and sequestrating CO_2.

No technology currently exists to use this enormous energy resource. Depressurisation, thermal stimulation and solvent injection are possible candidates for commercial exploitation – but a prerequisite would be to develop tools for identifying and characterising concentrated deposits. If a technology were to be developed, it could have, with respect to climate change, a kind of Janus' double face. On the one hand, it could prolong the era of fossil fuels and ultimately add a supplementary 10 000 Pg of carbon into the atmosphere (on top of the 5 000 Pg from the combustion of the currently known fossil resource base). Absent associated developments of CO_2 capture and storage technologies, such uses would imply an increase in atmospheric concentrations of up to 20-fold (substantially higher than the seven-fold increase projected with full combustion of current resources). On the other hand, such developments could stimulate the near-term replacement of coal and oil[6].

Unconventional gas reserves are usually more costly to exploit, but their associated CO_2 emissions are often much lower per unit of energy than those of other gas reserves. In some cases, as with coal-bed methane, recovery reduces methane emissions – with their larger-than-CO_2 global warming potential. However, the case for gas is not unequivocally positive: in some cases, (even in conventional gas), resources contain a high share of CO_2, sulphur or other toxic compounds that require large amounts of energy to clean – thus increasing the effective carbon intensity of these resources.

It must be noted that a number of countries are switching away from zero-emitting sources to fossil fuels. This is the case in several OECD countries that are currently phasing out nuclear power; it is also the case in a number of developing countries that are expanding energy supplies (for example, in Brazil, where constraints on hydro power are prompting the development of thermal generation facilities). Still other countries, seeing considerable volatility in gas prices, are reconsidering the option to build new coal-fired thermal generation.

7.3 Increased efficiency of conversion

While efficient combined cycle gas turbine currently represent state-of-the art of power generation with natural gas, there still are a range of technologies used for existing and new plants using coal, which exhibit diverse energy efficiency – and CO_2 emissions – performances.

Electricity generation accounted for 39 per cent of global carbon emissions in 2000. Baseline scenarios anticipate emissions of 3.5 GtC and 4 GtC for 2010 and 2020, respectively. The IPCC sets the potential for reductions at 350-700 MtC by 2020. Focusing on OECD Member countries, IEA's "Alternative Policy Case" predicts possible CO_2 emission reductions below reference scenarios of 4 per cent in 2010, 15 per cent in 2020, and 25 per cent in 2030 in these countries.

Prospects might be brighter in developing countries, where large investments in the power sector will be needed. Over the next twenty years, China and India alone are expected to build up to 500 and 200 GW respectively of new power generation capacity, of which at least 350 and 125 GW will be new coal plants. These new plants will partially replace older ones, thus increasing the average energy efficiency of the sector. However, if new capacities were of an advanced super-critical design rather than the classical sub-critical design, their efficiency would be increased by a further seven percentage points and their CO_2 emissions reduced by about 15 per cent compared to current projections. Here, the critical issue may not be costs, but technology transfer, as even with low coal prices, subsequent fuel savings would pay for the incremental cost of investing in the most efficient technology.

Further CO_2 reductions and energy efficiency increases will be possible using more advanced concepts such as "ultra-ultra" super-critical plants, fluidised bed combustion processes. Integrated gasification combined cycle power generation may offer longer term prospects, although existing pilot plants have thus far failed to demonstrate high energy efficiencies.

Another important way to raise the efficiency of energy use is simply to use the heat that cannot be converted into electricity in "combined heat and power" (CHP) systems. Electrification has in general

6 Gas hydrates may contain three orders of magnitude more methane than exists in today's atmosphere. Because hydrate breakdown, causing release to the atmosphere, can be related to global temperature increases, gas hydrates may play an even more important role in global climate change.

many advantages, including for raising efficiency in end-use processes. However, burning fossil fuels to create heat, converting that heat into electricity, and then using this electricity to produce heat for end-users is not a very efficient way of doing things. Thus, only combined heat and power raises efficiency higher than approximately 50% (in single cycle machines) or 60% (in combined cycles). It has been estimated that CHP might reduce CO_2 emissions by 20 to 40% - depending on the assumptions made on the reference case. Stationary fuel cells could also provide distributed combined heat-and-power.

More than 80% of current CHP capacity is used in large industrial applications, mostly in four sectors: paper, chemicals, petroleum refining, and food processing. Further CHP expansion in industry and commercial and residential sectors would be facilitated by more distributed energy systems, where power generation is closer to end-users. While recent IEA analyses finds that distributed generation is not yet ready to replace existing systems, there are changes to regulations and market rules which could promote a larger role (IEA, 2002e).

7.4 Non-carbon energy sources

Non-carbon energy sources are nuclear power (from fission and, perhaps, fusion), and renewable forms of energy. According to a recent IEA document (IEA, 2003b), three renewable energy technologies that could play a particularly significant role in future energy systems are offshore wind technology, concentrating solar power systems producing both electricity and heat, and bioenergy systems. All these options are considered below.

7.4.1 Nuclear power

Nuclear power accounts for about 7.3 per cent of world total primary energy supply, a sharp increase since 1973 (when it provided a mere 0.9 per cent). However, this growth has stalled in recent years, mainly because lower fossil-fuel prices have made coal- and gas-fired generation more attractive economically, and also because of increasing public concern, heightened after the Chernobyl accident in 1986. The IEA projects that the nuclear sector will continue to lose its share in the world energy mix after 2005 as older plants are retired. Other than in Asia, relatively few new plants are being proposed or built. However, nuclear plant life extension is progressively being introduced and may delay the future decline in installed nuclear capacity. There are also signs of a renewed interest for nuclear power in some countries (e.g., USA, South-Africa).

Existing, fully amortised nuclear power plants generally are competitive owing to their low marginal production costs. However, new nuclear power plants are seldom the choice of the market because of their high capital costs and related large financial risk. The longer term future of nuclear power will primarily depend on whether it can be competitive in future electricity markets; of particular importance will be reducing capital costs. The availability of final repositories for all types of radioactive waste, enhancements of nuclear safety as well as improved proliferation resistance measures would improve public acceptance of the technology.

Current “evolutionary” technical development efforts tend to build on experience gained with light water reactors to simultaneously reduce costs and increase safety, in particular by incorporating more passive safety features. The European Pressurised Reactor (EPR) project is a good representative of this category. Innovative designs may also become attractive (IEA *et al.*, 2002); for example, the gas-cooled Pebble Bed Modular Reactor (PBMR), based upon a design developed earlier in the USA and Germany, is being considered today by Eskom for construction in South Africa and possibly elsewhere. The modularity and small size of the PBMR may help its deployment in deregulated markets in spite of the 'loss of scale' effect as compared with large size plants..

Known uranium resources are sufficient for many decades at the present rate of nuclear electricity generation. However, a large increase of nuclear power capacity and electricity generation would require the development of more efficient fuel cycle technologies, such as breeding and the use of thorium. Active R&D and D programmes on these advanced systems, which are proven in principle, are being pursued in several countries, including France, Japan and the USA (NEA, 2002a and 2002b)**.** Nuclear fusion could be an option in the second half of this century if technical feasibility were demonstrated within a 20-30 year time scale.

7.4.2 Wind

Wind, solar and other renewable energy sources such as geothermal and tidal energies provide only 0.5 per cent of global demand for energy. Wind power is the fastest growing energy source – albeit from a very low base. In high wind areas, wind power is competitive with other forms of electricity generation. Global economic potential estimates vary from 20,000 TWh/y to over 40,000 TWh/y.

The development of wind resources confronts three key limits: costs, declining public acceptance of on-shore facilities, and intermittence. Costs have been constantly decreasing in the recent past, with technical improvements more than compensating for the increasing use of "second-best sites" (measured in terms of the quality of their wind resource). However, the current large deployment of wind turbines in Germany, Spain, the US, Denmark or India has only been made possible thanks to public subsidies that have priced wind power more competitively than fossil-fuelled electricity. Only continuous technical improvements will allow wind to be fully competitive.

The problem of public acceptance of wind turbines, while it varies from country to country, implies that the future of wind power may lie in offshore waters. The largest existing offshore wind farm, with a capacity of 160 MW, was connected to the grid in Denmark last December. The European Wind Energy Association targets for the EU include an installed capacity of 150 GW in 2020 (against 20 GW in 2002), of which 50 GW would be offshore (against less than 1 GW in 2002).

Offshore wind farms cost 30% to 70% more to build, operate and connect to the grid, but may access more regular wind resource and produce up to 50% more energy – simultaneously alleviating public acceptance and intermittence problems. Technical improvements and new concepts, such as floating platforms, might offer a large potential for reducing the up-front cost gap between onshore and offshore facilities.

The limits arising from the intermittent character of wind is disputed, and may vary with countries' situations. Denmark, now considering adding 4,000 MW of offshore wind turbines (to be in place by 2030) in addition to 1,500 MW onshore, will become a test case. If all facilities are constructed, wind power would provide about half of the country's electricity – and from time to time 100% of the needed power (capacity). Currently, the solution to the intermittence problem is to provide guaranteed back-up capacity. In the case of Denmark, this is likely to be fossil-fuelled. However, when larger systems are integrated, and full electricity interconnectivity is possible, (e.g., with Danish integration into the Scandinavian interconnected grid, largely fed by hydropower), such backup capacity could be provided in the system with no increase in emissions.

Currently, however, the general assumption is that there is a limit; most analysts suggest that only about 20% of peak demand can be provided from wind for the electricity mix to remain manageable. Proposals for addressing this limit are varied, and include options for energy storage – such as the use of wind power to produce hydrogen from seawater by electrolysis, as per an experiment being conducted by Japan's National Institute for Environmental Studies this year.

7.4.3 Solar

Solar energy received by the planet is about 9,000 times current energy consumption. Even though its technical potential is much less (and depends on factors such as land availability), lower estimates for supply exceed current global energy use by a factor of four. But the market potential for capture is currently low because of high costs, investment lead times and geographic variations. The diffuse, intermittent and non-dispatchable character of solar energy suggests it may remain a marginal technology unless storage becomes much cheaper (e.g., through hydrogen production). In addition, progress in superconductivity could be a key.

Solar electricity represents only 0.05 per cent of total electricity from renewable energy sources. Photovoltaic systems and concentrating solar-thermal power plants have approximately equal shares (Observ'ER-EDF, 2002). PV systems provide expensive energy but have niche markets, from remote consumers (including a share of the estimated one and a half billion people without access to electricity) to integration into building structures.

Building integrated photovoltaics offers a significant electric potential, evaluated by Gutschner *et al.*, 2001 for most IEA member countries. It could represent significant shares of electricity consumption, ranging from 15% (Japan) or 19% (Finland, Sweden) to 30% (UK, Germany, Canada), 45% or more (Australia, Italy, Spain) and up to 58% (the US). However, large reductions in costs and innovative storage systems are still needed for this source to compete with fossil-fuelled power plants – even taking into account some pricing of avoided externalities such as carbon dioxide.

Concentrating technologies may offer the best prospects for economically competitive large-scale production where solar resources are sufficiently intense. Nine plants in the Mojave Desert close to Los Angeles have provided 354 MWe of power since 1989. Concentrating technologies address intermittence problems through back up from fossil fuels or heat storage. While they offer much cheaper electricity than PV, prices are still higher than those of fossil fuels. However, in spite of higher prices, new projects are currently underway in Egypt, India, Mexico and Morocco with financing by the Global Environment as well as in Algeria, Greece Iran, Israel, Italy, Jordan, South Africa, Spain, and the U.S (see, e.g., www.solarpaces.org and www.enea.it).

In the future, concentrating solar technologies might be used to produce hydrogen or other energy carriers. For example, direct steam-reforming of natural gas with solar concentrated heat could produce exportable hydrogen for other consuming regions while halving CO_2 emissions and making capture and storage of remaining emissions relatively easy and cheap. At higher temperature in solar towers, photolysis or hydrocarbon cracking becomes options, producing only hydrogen and pure, non-oxidised carbon (Steinfeld & Palumbo, 2001).

7.4.4 Biomass

Combustible renewable energy sources, including waste, provide 11 per cent of world total primary energy supply – equal to its share in 1973. The growing of biomass on a sustainable basis leads to no net build-up of CO_2 in the atmosphere, because CO_2 released in combustion is balanced by CO_2 extracted from the atmosphere during photosynthesis. However, analysis suggests that biomass use may soon start declining. For health, local environmental and sometimes growing scarcity reasons, renewable combustibles are often replaced by more efficient fossil fuel sources in poor households in developing countries. A possible source of progress could be the development of household stoves with improved combustion (rather than enhanced thermal efficiency only) to reduce indoor pollution and health risks for users (RWEDP, 2000). While such end use options are not “high-tech”, they are still of potentially significant importance in many developing countries.

Developments in technology may reverse the trends toward a decline in the use of biomass, particularly as biomass finds its way into the power sector, in particular through gasification. Current agricultural and forestry practices may provide considerable biomass volumes from crop residues as well as from areas specifically cultivated for biomass energy production. However, photosynthesis is a relatively inefficient process (in terms of energy output by solar input on a given surface) and land availability will put an upper limit on what might reasonably be expected from biomass as an energy source.

Biofuels may also be used as a replacement for gasoline. In such a capacity they offer significant advantages for energy security as well as possible new potential for agricultural development. However, biofuels substitution is a costly means to reduce CO_2 emissions, and recent analyses (see, e.g., Azar *et al*., 2003) suggest that biomass would be more effectively used for heat and process heat during the coming decades.

7.4.5 Other renewable energies

Hydropower provides 2.3 per cent of current global energy demand. Hydropower is expected to increase in absolute quantities over the next two decades, and its economic potential world-wide remains important. However, its development remains largely dependent on resolving public concerns about the environmental and social consequences of building new facilities – particularly large dams. Another important barrier is the increasing distance between still non-exploited resources and potential consumers. Progress in superconductivity could be a key for further development.

Other renewable energy applications include a variety of solar applications (e.g., solar hot water, solar space heating, solar drying of agricultural crops, solar cooling, passive solar energy use in heating and cooling buildings), as well as geothermal energy and marine energy (e.g., wave, ocean current, ocean thermal and tidal). Some of these sources are already competitive – notably hot water and passive solar use in buildings. However, even collectively, these are not estimated to provide a significant share of the energy demand over the next twenty years. It may be, though, that commercial energy statistics hide some uses of solar energy (such as heating buildings) that tend to be merged with energy savings. As with many of the renewable energy options, given the current and projected low levels of use, it will take considerable policy “push” to stimulate the growth of such technologies to an appreciable market share over the next thirty to fifty years.

7.5 CO_2 capture and storage

Various technologies are now available for CO_2 separation, transport and underground storage, although costs remain high, and the long-term environmental consequences are not entirely certain. Currently, these technologies are best suited to dealing with emissions of large point sources of CO_2, such as power plants and energy-intensive industries, rather than small, dispersed sources such as transport and heating.

Both pre- and post-combustion technologies exist for CO_2 capture. Post-combustion CO_2 capture uses amine solvents to scrub the flue-gases. The amine leaving the scrubber is heated to release high-purity CO_2 and is then re-used. However, the low concentration of CO_2 in the power-station flue-gases means that a very large volume of flue-gas has to be treated. Equipment is thus large – and large amounts of energy are required for solvent generation.

A pre-combustion capture technology avoids many of these problems – but necessitates using hydrogen more widely as an energy carrier. Pre-combustion capture may have the highest potential value when used for oil and, above all, coal, given the abundance, cost and world distribution of this resource. In addition, extraction of CO_2 is more costly for natural gas.

Both pre and post combustion CO_2 capture might be greatly facilitated by oxyfuel combustion. Fossil fuels are burnt in an oxygen and recycled flue gas mixture instead of air. This generates a high purity CO_2 flue gas stream that can be captured more easily. In addition, NOx emissions are greatly reduced. Oxyfuel combustion can be an attractive option for the retrofit of existing steam cycle power stations. However, oxyfuel combustion incurs the penalty of upstream air separation for oxygen production, which requires high capital investments and high-energy penalties with today's technologies.

Associating CO_2 capture and storage with biomass use for heat, electricity or hydrogen production may seem particularly desirable, as the cycle would pump carbon out of the atmosphere. Each carbon tonne stored would have a double value. However, in a world with positive net emissions, CO_2 capture should be undertaken where it is the most cost-effective – more likely to be in association with coal than with biomass, given in particular the larger optimal size of coal plants.

IPCC estimates for storage capacities range from 1,500 to 14,000 GtC; this scale suggests that storage is not likely to be a major constraint on CO_2 removal and sequestration potential, provided current knowledge is improved and long-term storage guaranteed. Storage in the deep ocean would further extend this capacity but raises serious environmental concerns.

Cost estimates vary with techniques, as well as with transport distances. They range from $25/tonne C to $60 /tonne C, including storage. As with most technologies, there is scope to reduce costs in the future through technical improvements. If the CO_2 is used for enhanced oil or coal bed methane recovery, some of the costs are offset – in fact in some cases there is a net benefit. Currently 8 million tonnes of carbon are injected annually for enhanced oil recovery, mostly in West Texas. This may be referred to as "value-added geologic sequestration".

For CO_2 storage to be an effective way of avoiding climate change, the CO_2 must be stored for several hundreds or thousands of years. CO_2 storage must also have low environmental impact, low cost and conform to national and international laws.

Emissions can be stored in depleted oil and gas reservoirs, unminable coal seams and deep saline reservoirs. CO_2 use in oil reservoirs for enhanced oil recovery, and CO_2 storage in depleted natural gas fields, are demonstrated technologies. CO_2 injection into coal seams for both storage and enhanced production of coal-bed methane is now being tested in pilot plants. However, oil and gas reservoirs and coal seams provide relatively limited storage capacity compared with projected needs. Underground storage of CO_2 in deep saline aquifers has been demonstrated in one commercial-scale project. Such aquifers represent a potentially huge and widely dispersed storage medium, but further effort is needed to provide convincing evidence that storage is safe and secure and to better understand various geological formations. Storage in the deep ocean has also been proposed, but several environmental and legal issues must be resolved before this can be a viable option. As CO_2 reacts with naturally occurring minerals, such as magnesium silicate, to produce carbonate rocks, injecting CO_2 into underground reservoirs containing minerals that would react with CO_2 could be a long term solution to the CO_2 problem.

Analyses suggest that stabilisation will be less costly if capture and storage are included in the mitigation options – but also reveal that leakage rates from underground reservoirs might be a critical issue. Dooley and Wise (2002) quote new MiniCAM modelling results that seek to find economically efficient ways to reach various stabilisation targets along the emission pathways suggested by Wigley *et al*. (1996). The model combines both capture and storage along with more extensvie use of non-carbon fuels and improving end-use efficiencies. Dooley and Wise report that the cumulative amount of carbon disposed of over this century would be about 100 GtC, 200 GtC and 340 GtC to reach concentration levels of 650, 550 and 450 ppm respectively.

However, different assumption about leakage rates would significantly modify the picture. Rates of leakage are unknown, and are likely to vary with different types of reservoirs, due to differing geologic characteristics but also differing histories of use: exploited fields, while more likely to offer possibilities for "value-added geologic sequestration" might also exhibit higher leakage rates. Dooley and Wise (2002) have calculated the effects of hypothetical leakage rates of 1% and 0.1% per year on emission pathways leading to stabilisation. They found that emissions allowed under the 550-ppm target with a 1% per year leakage rate approaches the much more stringent 450-ppm target by the end of the century. The 450-ppm could only be met with negative emissions by 2060. Leakage explains "*why injecting CO_2 into various geological formation is not the same as climate change mitigation*" (Dooley and Wise, 2002). Such rates, however, are highly speculative, and may considerably exceed the capacity of geological storage.

Recent analysis suggests assessing the value of "temporary storage". If carbon prices remain constant (or if there is a backstop technology that caps the abatement cost in the not too distant future), even relatively temporary storage such as that provided by deep ocean carbon sequestration would be nearly equivalent to permanent sequestration. If, on the contrary, a fixed cumulative emissions limit were required and there is no backstop, then storage options with even very low leakage have limited value (Herzog *et al*., 2003). While the emergence of a backstop technology that would dominate current fossil fuel-based technologies cannot be taken for granted, even long-term CO_2 concentration stabilisation will allow for some CO_2 emissions. These levels may be compatible with leakage from geological storage. Clearly, this area needs further research.

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