Chapter 4. What Are the Options and Measures That Could Significantly Affect the Carbon Cycle?

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KEY FINDINGS

• Options to reduce energy-related CO₂ emissions include improved efficiency, fuel switching (among fossil fuels and non-carbon fuels), and CO₂ capture and storage.

• Most energy use, and hence energy-related CO₂ emissions, involves equipment or facilities with a relatively long life—5 to 50 years. Many options for reducing these CO₂ emissions are most cost-effective, and sometimes only feasible, in new equipment or facilities. This means that cost-effective reduction of energy-related CO₂ emissions may best be achieved as existing equipment and facilities are replaced. It also means that technological change will have a significant impact on the cost because emission reductions will be implemented over a long time.

• Options to increase carbon sinks include forest growth and agricultural soil sequestration. The amount of carbon that can be captured by these options is significant, but small relative to the excess carbon in the atmosphere. These options can be implemented in the short-term, but the amount of carbon sequestered typically is low initially then rising for a number of years before tapering off again as the total potential is achieved. There is also a significant risk that the carbon sequestered may be released again by natural phenomena or human activities.

• A number of policy options can help reduce carbon emissions and increase carbon sinks. The effectiveness of a policy depends on the technical feasibility and cost-effectiveness of the portfolio of measures it seeks to promote, on its suitability given the institutional context, and on its interaction with policies implemented to achieve other objectives.

• Policies to reduce atmospheric CO₂ concentrations cost effectively in the short- and long-term would: (1) encourage adoption of cost-effective emission reduction and sink enhancement measures through an emissions trading program or an emissions fee; (2) stimulate development of technologies that lower the cost of emissions reduction, geological storage and sink enhancement; (3) adopt
appropriate regulations to complement the emissions trading program or emission fee for sources or actions subject to market imperfections, such as energy efficiency measures and co-generation; (4) Revise existing policies with other objectives that lead to higher CO₂ or CH₄ emissions so that the objectives, if still relevant, are achieved with lower emissions.

- Implementation of such policies is best achieved by national governments with international cooperation. This provides maximum coverage of CO₂ emissions and carbon sinks and so enables implementation of the most cost-effective options. It also allows better allocation of resources for technology research and development. National policies may need to be coordinated with state/provincial governments, or state/provincial governments may implement coordinated policies without the national government.

INTRODUCTION

This chapter provides an overview of measures that can reduce CO₂ and CH₄ emissions and those that can enhance carbon sinks, and it attempts to compare them. Finally, it discusses policies to encourage implementation of source reduction and sink enhancement measures.

SOURCE REDUCTION OPTIONS

Combustion of fossil fuels is the main source of CO₂ emissions, although some CO₂ is also released in non-combustion and natural processes. Most energy use, and hence energy-related CO₂ emissions, involves equipment or facilities with a relatively long life—5 to 50 years. Many options for reducing these CO₂ emissions are most cost-effective, and sometimes only feasible, in new equipment or facilities.

To stabilize the atmospheric concentration of CO₂ “would require global anthropogenic CO₂ emissions to drop below 1990 levels . . . and to steadily decrease thereafter” (IPCC, 2001a).¹ That entails a transition to an energy system where electricity and hydrogen become the major energy carriers. They are produced by non-fossil sources or from fossil fuels with capture and geological storage of the CO₂ generated. The transition to such an energy system, while meeting growing energy needs, will take at least several decades. Thus, shorter term (2015–2025) and longer term (post-2050) options are differentiated.

Options to reduce energy-related CO₂ emissions can be grouped into a few categories:

- efficiency improvement,

¹The later the date at which global anthropogenic CO₂ emissions drop below 1990 levels, the higher the level at which the CO₂ concentration is stabilized.
• fuel switching to fossil fuels with lower carbon content per unit of energy produced and to non-
carbon fuels, and

• switching to electricity and hydrogen produced from fossil fuels in processes with CO2 capture and
geological storage.

**Efficiency Improvement**

Energy is used to provide services such as heat, light, and motive power. Any measure that delivers
the desired service with less energy is an efficiency improvement. Efficiency improvements reduce CO2
emissions whenever they reduce the use of fossil fuels directly or indirectly. Energy use can be reduced
by improving the efficiency of individual devices (such as refrigerators, industrial boilers, and motors), by
improving the efficiency of systems (using the correct motor size for the task), and by using energy that is
not currently utilized, such as waste heat. Opportunities for efficiency improvements are available in all
sectors.

It is useful to distinguish two levels of energy efficiency improvement: (1) the amount consistent with
efficient utilization of resources (the economic definition) and (2) the maximum attainable (the
engineering definition). Energy efficiency improvement thus covers a broad range, from measures that
provide a cost saving to measures that are too expensive to warrant implementation. Market imperfections
inhibit adoption of some cost-effective efficiency improvements (NCEP, 2005).

Energy efficiency improvements tend to occur gradually, but steadily, across the economy in response
to technological developments, replacement of equipment and buildings, changes in energy prices, and
other factors. In the short term, the potential improvement depends largely on greater deployment and
use of available efficient equipment and technology. In the long term, it depends largely on technological
developments.

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2 In the transportation sector, for example, energy efficiency can be increased by improving the fuel performance of vehicles,
shifting to less emissions-intensive modes of transport, and adopting measures that reduce transportation demand, such as
telecommuting and designing communities so that people live closer to shopping and places of work.

3 Increasing the fuel economy of vehicles or the efficiency of coal-fired generating units reduces fossil fuel use directly.
Increasing the efficiency of refrigerators reduces electricity use and hence the fossil fuel used to generate electricity.

4 For example, 40 to 70% of the energy in the fuel used to generate electricity is wasted. Cogeneration or combined heat
and power systems generate electricity and produce steam or hot water. Cogeneration requires a nearby customer for the steam or
heat.

5 Examples include limited foresight, externalities, capital market barriers, and principal/agent split incentive problems.

6 The rate of efficiency improvement varies widely across different types of equipment such as lighting, refrigerators, electric
motors, and motor vehicles.
Fuel Switching

Energy-related CO₂ emissions are primarily due to combustion of fossil fuels. Thus, CO₂ emissions can be reduced by switching to a less carbon-intensive fossil fuel or to a non-carbon fuel.

The CO₂ emissions per unit of energy for fossil fuels (carbon intensity) differ significantly, with coal being the highest, oil and related petroleum products about 25% lower, and natural gas over 40% lower than coal. Oil and/or natural gas can be substituted for coal in all energy uses, mainly electricity generation. However, natural gas is not available everywhere in North America and is much less abundant than coal, limiting the large-scale long-term replacement of coal with natural gas. Technically, natural gas can replace oil in all energy uses but to substitute for gasoline and diesel fuel, by far the largest uses of oil, would require conversion of millions of vehicles and development of a refueling infrastructure.

Non-carbon fuels include
- biomass and fuels, such as ethanol, produced from biomass; and
- electricity and hydrogen produced from carbon-free sources.

Biomass can be used directly as a fuel in some situations. Pulp and paper plants and sawmills, for example, use wood waste and sawdust as fuel. Ethanol, currently produced mainly from corn, is blended with gasoline. The CO₂ emission reduction achieved depends on whether the biomass used is replaced, on the fossil-fuel energy used to produce the fuel, and the carbon content of the fuel displaced.

Carbon-free energy sources include hydro, wind, solar, biomass, geothermal, and nuclear fission. Sometimes they are used to provide energy services directly, such as solar water heating and wind mills for pumping water. But they are mainly used to generate electricity, about 35% of the electricity in North America. Currently, generating electricity using any of the carbon-free energy sources is usually more costly than using fossil fuels.

Most of the fuel switching options are currently available, and so are viable short-term options in many situations.

Electricity and Hydrogen from Fossil Fuels with CO₂ Capture and Geological Storage

About 65% of the electricity in North America is generated from fossil fuels, mainly coal but with a rising share for natural gas (EIA, 2003). The CO₂ emissions from fossil-fired generating units can be captured and injected into a suitable geological formation for long-term storage.

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7 Reservoirs for hydroelectric generation produce CO₂ and methane emissions, so such sources are not totally carbon free.
Hydrogen (H\textsubscript{2}) is an energy carrier that emits no CO\textsubscript{2} when burned, but may give rise to CO\textsubscript{2} emissions when it is produced (National Academies, 2004). Currently, most hydrogen is produced from fossil fuels in a process that generates CO\textsubscript{2}. The CO\textsubscript{2} from this process can be captured and stored in geological formations. Alternatively, hydrogen can be produced from water molecules using electricity, in which case the CO\textsubscript{2} emissions depend on how the electricity is generated. Hydrogen could substitute for natural gas in most energy uses and be used by fuel cell vehicles.

Carbon dioxide can be captured from the emissions of large sources, such as power plants, and pumped into geologic formations for long-term storage, thus permitting continued use of fossil fuels while avoiding CO\textsubscript{2} emissions to the atmosphere.\textsuperscript{8} Many variations on this basic theme have been proposed; for example, pre-combustion vs post-combustion capture, production of hydrogen from fossil fuels, and the use of different chemical approaches and potential storage reservoirs. While most of the basic technology exists, much work remains to safely and cost effectively integrate CO\textsubscript{2} capture and storage into our energy system, so this is mainly a long-term option (IPCC, 2005).

\textbf{Industrial Processes}

The processes used to make cement, lime, and ammonia release CO\textsubscript{2}. Because the quantity of CO\textsubscript{2} released is determined by chemical reactions, the process emissions are determined by the output. But, the CO\textsubscript{2} could be captured and stored in geological formations. CO\textsubscript{2} also is released when iron ore and coke are heated in a blast furnace to produce molten iron, but alternative steel-making technologies with lower CO\textsubscript{2} emissions are commercially available. Consumption of the carbon anodes during aluminum smelting leads to CO\textsubscript{2} emissions, but good management practices can reduce the emissions. Raw natural gas contains CO\textsubscript{2} that is removed at gas processing plants and could be captured and stored in geological formations.

\textbf{Methane Emissions}

Methane is produced as organic matter decomposes in low-oxygen conditions and is emitted by landfills, wastewater treatment plants, and livestock manure. In many cases, the methane can be collected and used as an energy source. Methane emissions also occur during production of coal, oil, and natural gas. Such emissions usually can be flared (though this generates CO\textsubscript{2}) or collected for use as an energy source. Ruminant animals produce CH\textsubscript{4} while digesting their food. Emissions by ruminant farm animals can be reduced by measures that improve animal productivity. All of these emission reductions are currently available.

\textsuperscript{8}Since combustion of biomass releases carbon previously removed from the atmosphere, capture and storage of these emissions results in negative emissions.
TERRESTRIAL SEQUESTRATION OPTIONS

Trees and other plants sequester carbon as biological growth captures carbon from the atmosphere and sequesters it in the plant cells (IPCC, 2000b). Currently, very large volumes of carbon are sequestered in the plant cells of the earth’s forests. Increasing the stock of forest through afforestation, reforestation, or forest management draws carbon from the atmosphere and increases the carbon sequestered in the forest and the soil of the forested area. Sequestered carbon is released by fire, insects, disease, decay, wood harvesting, conversion of land from its natural state, and disturbance of the soil.

Agricultural practices can increase the carbon sequestered by the soil. Some crops build soil organic matter, which is largely carbon, better than others. Some research shows that crop-fallow systems result in lower soil carbon content than continuous cropping systems. No-till and low-till cultivation builds soil organic matter.

Conversion of agricultural land to forestry can increase carbon sequestration in soil and tree biomass, but the rate of sequestration depends on the soil type. Conversion of agricultural land to other uses can result in positive or negative net carbon emissions depending upon the land use.

Although forest growth and soil sequestration cannot capture all of the excess carbon in the atmosphere, they do have the potential to capture a significant portion. These options can be implemented in the short-term, but the amount of carbon sequestered typically is low initially then rising for a number of years before tapering off again as the total potential is achieved.

INTEGRATED COMPARISON OF OPTIONS

As is clear from the previous sections, there are thousands of options to reduce emissions of or to sequester CO₂. To help them decide which options to implement, policy makers need to know which are the most cost-effective—have the lowest cost per metric ton of CO₂ reduced or sequestered.

This involves an integrated comparison of options, which can be surprisingly complex in practice. It is most useful and accurate for short-term options where the cost and performance of the option can be forecast with a high degree of confidence. The performance of many options is interrelated; for example, the emission reductions that can be achieved by blending ethanol in gasoline depend on other measures as well, such as telecommuting, to reduce travel demand the success of modal shift initiatives, and the efficiency of motor vehicles. The prices of fossil fuels affect the cost-effectiveness of many options.

9The IPCC (2001b) estimated that biological growth including soils has the potential of capturing up to 20% of the globe’s releases of excess atmospheric carbon over the next 50 years (Chapter 4). Nabuurs et al. (2000) estimate potential annual forest sequestration in the United States at 6% to 11% of 1990 emissions and 125% to 185% of 1990 emissions for Canada. For the two countries together, the figure is 17% to 27%.
Changes to the age structure of the population, increases in per capita incomes, and other factors can affect the potential for some options as well. Finally, the policy selected to implement an option, incentives vs a regulation for example, can affect its potential.

The emission reduction potential and cost-effectiveness of options also vary by location. Energy sources and sequestration options differ by location; for example, natural gas may not be available, the wind and solar regime vary, hydro potential may be small or large, land suitable for afforestation/reforestation is limited, the agricultural crops may or may not be well suited to low-till cropping. Climate, lifestyles, and consumption patterns also affect the potential of many options; for example, more potential for heating options in a cold climate, more for air conditioning options in a hot climate. The mix of single-family and multi-residential buildings affects the potential for options focused on those building types, and the scope for public transit options tends to increase with city size.

Institutional factors affect the potential of many options as well; for example, the prevalence of rented housing affects the potential to implement residential emission reduction measures, the authority to specify minimum efficiency standards for vehicles, appliances, and equipment may rest with the state/provincial government or the national government, and the ownership and regulatory structure for gas and electric utilities can affect their willingness to offer energy efficiency programs.

The estimated cost and emission reduction potential for the principal short-term CO₂ emission reduction and sequestration options are summarized in Table 4.1. All estimates are standardized to a common unit of measurement—2004 U.S. dollars per metric ton of carbon.¹⁰

### Table 4-1. Standardized cost estimates [annualized cost in 2004 constant U.S. dollars per metric ton of carbon (t C)]

Most options have a range of costs. The range is due to four factors. First, the cost per unit of emissions reduced varies by location even for a very simple measure. For example, the emission reduction achieved by installing a more efficient light bulb depends on the hours of use and the generation mix that supplies the electricity. Second, the cost and performance of any option in the future is uncertain. Different assumptions about future costs and performance contribute to the range. Third, most mitigation and sequestration options are subject to diminishing returns, that is, cost rises at an increasing rate with greater use, as in the power generation, agriculture, and forestry cost estimates. So the estimated scale of

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¹⁰A metric ton (sometimes written as “tonne”) is 1000 kg, which is 2205 lb or 1.1025 tons.
adoption contributes to range. Finally, some categories include multiple options, notably those for the
U.S. economy as a whole, each with its own marginal cost. For example, the “All Industry” category is an
aggregation of seven subcategories discussed in Chapter 8. The result again is a range of cost estimates.
The cost estimates in Table 4-1 are the direct costs of the options. A few options, such as the first
estimate for power generation in Table 4-1, have a negative annualized cost. This implies that the option
mitigation is likely to yield cost savings for reasons such as improved combustion efficiency. Some
options have ancillary benefits (e.g., reductions in ordinary pollutants, reduced dependence on imported
oil, expansion of wildlife habitat associated with afforestation) that reduce their cost from a societal
perspective. Indirect (multiplier, general equilibrium, macroeconomic) effects in the economy tend to
increase the direct costs (as when the increased cost of energy use raises the price of products that use
energy or energy-intensive inputs). Examples of these complicating effects are presented in individual
chapters, along with some estimates of their effects on costs.

As indicated in several segments of Table 4.1, costs are sensitive to the policy instrument used to
implement the option. In general, the less restrictive the policy, the lower the cost. That is why the cost
estimates for the Feebate are lower than the cost estimate for the CAFÉ standard. In a similar vein, costs
are lowered by expanding the number of participants in a permit trading arrangement, especially those
with a prevalence of low-cost options, such as developing countries. That is why the global trading costs
are lower than the Annex I (industrialized countries only) case for the U.S. economy.

The task of choosing the “best” combination of options may seem daunting given the numerous
options and the associated cost ranges. This combination will depend on several factors including the
emission target, the emitters covered, the compliance period, and the ancillary benefits of the options. The
best combination will change over time as cheap options become more costly with additional
installations, and technological change lowers the costs of more expensive options. It is unlikely that
policy-makers can identify the least-cost combination of options to achieve a given emission target. They
can adopt policies, such as permit trading, that cover a large number of emitters and allow them to choose
the lowest cost reduction options.

POLICY OPTIONS

Overview

Stabilizing the carbon cycle will require very substantial reductions and increased sequestration of
CO₂ emissions. Policies will need to stimulate implementation of a portfolio of options to reduce
emissions and increase sequestration in the short-term, taking into account constraints on and implications
of the mitigation strategies. Policies will also need to encourage research and development of
technologies that can reduce emissions even further in the long term.
No single technology or approach can achieve a sufficiently large CO₂ emission reduction or sequestration to stabilize the carbon cycle (Hoffert et al., 1998, 2002). A portfolio of options will need to be implemented, including greater efficiency in the production and use of energy; expanded use of renewable energy technologies; technologies for removing carbon from fossil fuels and sequestering it in geological formations; various changes in forestry, agricultural, and land use practices; and possibly other approaches, some of which are currently very controversial, such as nuclear power and certain types of “geoengineering.”

Because CO₂ has a long atmospheric residence time,¹¹ immediate action to reduce emissions and increase sequestration allows its atmospheric concentration to be stabilized at a lower level.¹² Policy instruments to promote cost-effective implementation of a portfolio of options covering virtually all emissions sources and sequestration options are available for the short term. Such policy instruments are discussed below.

General Considerations

Policies to encourage reduction and sequestration of CO₂ emissions could include information programs, voluntary programs, conventional regulation, emissions trading, and emissions taxes (Tietenberg, 2000). Information and voluntary programs are generally not environmentally effective¹³ (OECD, 2003b).

Reducing emissions will require the use of policy instruments such as regulations, emissions trading, and emissions taxes. Regulations can require designated sources to keep their emissions below a specified limit, either a quantity per unit of output or an absolute amount per day or year. Regulations can also stipulate minimum levels of energy efficiency of appliances, buildings, equipment, and vehicles.

An emissions trading program establishes a cap on the annual emissions of a set of sources. Allowances equal to the cap are issued and can be traded. Each source must monitor its actual emissions and remit allowances equal to its actual emissions to the regulator. An emissions trading system creates an incentive for sources with low-cost options to reduce their emissions and sell their excess allowances. Sources with high-cost options find it less expensive to buy allowances at the market price than to reduce their own emissions enough to achieve compliance.

¹¹CO₂ has an atmospheric lifetime of 5 to 200 years. A single lifetime can not be defined for CO₂ because of different rates of uptake by different removal processes. (IPCC, 2001a, Table 1, p. 38)
¹²IPCC, 2001a, p. 187.
¹³Information and voluntary programs may have some impact on behavior through an appeal to patriotism or an environmental ethic; publishing information that may reveal negative actions, as in a pollutant registry; and providing public recognition, as in green labeling or DOE’s Energy Star Program (Tietenberg and Wheeler, 2001).
An emissions tax requires designated sources to pay a specified levy for each unit of its actual emissions. In a manner analogous to emissions trading, emitters will mitigate emissions up to the point where mitigation costs are lower than the tax, but once mitigation costs exceed the tax they will opt to pay it.

The choice of policy instrument needs to consider institutional and socioeconomic constraints that affect its implementation, such as the ability of sources to monitor their actual emissions, the constitutional authority of national and/or provincial/state governments to impose emissions taxes, regulate emissions and/or regulate efficiency standards. It is also important to consider potential conflicts between carbon reduction policies and policies with other objectives, such as keeping energy costs to consumers as low as possible.

Practically every policy (except cost-saving conservation and other “no regrets” options), no matter what instrument is used to implement it, has a cost in terms of utilization of resources and ensuing price increases that leads to reductions in output, income, and employment, or in more technical measures of economic well-being (e.g., “welfare measures” such as “compensating variation”). The total cost is usually higher than the direct cost due to interactions with other segments of the economy (“general equilibrium” effects) and with existing policies. Regardless of where the compliance obligation is imposed, the cost ultimately is borne by the general public as consumers, shareholders, employees, taxpayers, and recipients of government services. The cost can have competitiveness impacts if some emitters in other jurisdictions are not subject to similar policies. But the societal benefits, such as improved public health and reduced environmental damage, may exceed the cost of implementing the policy.

To achieve a given emission reduction target, regulations that require each affected source to meet a specified emissions limit or implement specified controls are almost always more costly than emissions trading or emissions taxes because they require each affected source to meet the regulation regardless of cost rather than allowing emission reductions to be implemented where the cost is lowest (Bohm and Russell, 1986). The cost saving available through trading or an emissions tax generally increases with the diversity of sources and share of total emissions covered by the policy.

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The source with the compliance obligation passes on the cost through some combination of higher prices for its products, negotiating lower prices with suppliers, layoffs, and/or lower wages for employees, and lower profits that lead to lower tax payments and lower share prices. Other firms that buy the products or supply the inputs make similar adjustments. Governments raise taxes or reduce services to compensate for the loss of tax revenue. Ultimately all of the costs are borne by the general public.

As well, regulation is generally inferior to emissions trading or taxes in inducing technological change.

These policies encourage implementation of the lowest cost emission reductions available to the affected sources. They establish a price (the emissions tax or the market price for an allowance) for a unit of emissions and then allow affected sources to respond to the price signal. In principle, these two instruments are equivalent in terms of achievement of the efficient allocation of resources, but they may differ in terms of equity because of how the emission permits are initially distributed and whether a tax or subsidy is used. It is easier to coordinate emissions trading programs than emissions taxes across jurisdictions.
(an emissions tax or auctioned allowances) has a lower macroeconomic cost than a policy that does not, if
the revenue is used to reduce existing distortionary taxes such as sales or income taxes (see, e.g., Parry
et al., 1999).

**Source Reduction Policies**

Historically CO\(_2\) emissions have not been regulated directly. Some energy-related CO\(_2\) emissions
have been regulated indirectly through energy policies, such as promotion of renewable energy, and
efficiency standards and ratings for equipment, vehicles, and some buildings. Methane emissions from oil
and gas production, underground coal mines, and landfills have been regulated, usually for safety reasons.

Policies with other objectives can have a significant impact on CO\(_2\) emissions. Policies to encourage
production or use of fossil fuels, such as favorable tax treatment for fossil fuel production, increase CO\(_2\)
emissions. Similarly, urban plans and infrastructure that facilitate automobile use rather than public transit
increase CO\(_2\) emissions. In contrast, a tax on vehicle fuels reduces CO\(_2\) emissions.

CO\(_2\) emissions are well suited to emissions trading and emissions taxes. These policies allow
considerable flexibility in the location and, to a lesser extent, the timing of the emission reductions. The
environmental impacts of CO\(_2\) depend on its atmospheric concentration, which is not sensitive to the
location or timing of the emissions. Apart from ground-level safety concerns, the same is true of CH\(_4\)
emissions. In addition, the large number and diverse nature of the CO\(_2\) and CH\(_4\) sources means that use of
such policies can yield significant cost savings.

Despite the advantages of emissions trading and taxes, there are situations where regulations setting
maximum emissions on individual sources or efficiency standards for appliances and equipment are
preferred. Such regulations may be desirable where monitoring actual emissions is costly or where firms
or individuals do not respond well to price signals due to lack of information or other barriers. Energy
efficiency standards for appliances, buildings, equipment and vehicles tend to fall into this category
(OECD, 2003a).

**Sequestration Policies**

Currently there are few, if any, policies whose primary purpose is to increase carbon uptake by forests
or agricultural soils. But policies designed to achieve other objectives, such as afforestation of marginal
lands, green payments, conservation compliance, Conservation Reserve Program, and CSP increase
carbon uptake. Policies that affect crop choice (support payments, crop insurance, disaster relief) and

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17. The efficiency of standards sometimes can be improved by allowing manufacturers that exceed the standard to earn credits
that can be sold to manufacturers that do not meet the standard.
farmland preservation (conservation easements, use value taxation, agricultural zoning) may increase or reduce the carbon stock of agricultural soils. And policies that encourage higher agricultural output (support payments) can reduce the carbon stored by agricultural soils.

Policies to increase carbon uptake by forests and agricultural soils could take the form of:

- Regulations, such as requirements to reforest areas that have been logged, implement specified forest management practices, and establish land conservation reserves;
- Incentive-based policies, such as subsidies for adoption of specified forest management or agricultural practices, or issuance of tradable credits for increases in specified carbon stocks. The tradable credits can be sold to sources subject to a CO₂ emissions trading program or offset requirement.¹⁸ Since the carbon is easily released from these sinks, for example by a forest fire or tilling the soil, ensuring the permanence of the carbon sequestered is a major challenge for such policies. (Feng et al., 2003);
- Voluntary actions, such as “best practices” that enhance carbon sequestration in soils and forests while realizing other benefits (e.g., managing forests for both timber and carbon storage), establishment of plantation forests for carbon sequestration, and increased production of wood products (Sedjo, 2001; Sedjo and Swallow, 2002).

The carbon cycle impacts of such programs would not be large, compared with emission levels; and in nearly every case they face serious challenges in verifying and monitoring the net carbon uptake, especially over relatively long periods (e.g., Marland et al., 2001).

Research and Development Policy

Policies to stimulate research and development of lower emissions technologies for the long term are also needed. Policies to reduce CO₂ emissions influence the rate and direction of technological change (OECD, 2003a). By stimulating additional technological change, such policies can reduce the cost of meeting a given reduction target (Goulder, 2004). Such induced technological change justifies earlier and more stringent emission reduction targets.

Two types of policies are needed to achieve a given cumulative CO₂ reduction or concentration target at least cost. Policies to reduce emissions and increase sequestration help are needed to create a market for less emission-intensive technologies. But direct support for research and development is also important; the combination of “research push” and “market pull” policies is more effective than either strategy on its own.

¹⁸Projects to increase forest sequestration are envisaged in the Kyoto Protocol through Articles 3.3 and 3.4 and through the use of the Clean Development Mechanism (CDM). Also, forests could create carbon offset credits that could be exchanged in tradable carbon systems. Some offset credits might be viewed as temporary. However, there are many circumstances where temporary credits would be valuable additions to a carbon reduction portfolio.
own (Goulder, 2004). Policies should encourage research and development for all promising technologies because there is considerable ambiguity about which ones will ultimately prove most useful, socially acceptable, and cost-effective.19

CONCLUSIONS

Policies to reduce projected CO2 and CH4 concentrations in the atmosphere must recognize the following:

- Emissions are produced by millions of diverse sources, most of which (e.g., power plants, factories, building heating and cooling systems, and large appliances) have lifetimes of 5 to 50 years, and so can adjust only slowly at reasonable cost;
- Potential uptake by agricultural soils and forests is significant but small relative to emissions and can be reversed easily;
- Technological change will have a significant impact on the cost because emission reductions will be implemented over a long time, and new technologies should lower the cost of future reductions; and
- Many policies implemented to achieve other objectives by different national, state/provincial, and municipal jurisdictions increase or reduce CO2/CH4 emissions.

The effectiveness of the policies is determined by the technical feasibility and cost-effectiveness of the portfolio of measures they seek to promote, their interaction with other policies that have unintended impacts on CO2 emissions, and by their suitability given the institutional and socioeconomic context (Raupach et al., 2004). This means that the effectiveness of the portfolio can be limited by factors such as:

- The institutional and timing aspects of technology transfer. The patenting system for instance does not allow all countries and sectors to get the best available technology.
- Demographic and social dynamics. Factors such as land tenure, population growth, and migration may pose an obstacle to reforestation strategies.
- Institutional settings. The effectiveness of taxes, subsidies, and regulations to induce the deployment of certain technology may be limited by factors such as corruption or existence of vested interests.
- Environmental considerations. The portfolio of measures may incur environmental costs such as waste disposal or biodiversity reduction.

Under a wide range of assumptions, cost-effective policies to reduce atmospheric CO2 and CH4 concentrations cost-effectively in the short and long term would

19 In other words, research and development is required for a portfolio of technologies. Because technologies have global markets, international cooperation to stimulate the research and development is appropriate.
Encourage adoption of cost-effective emission reduction and sink enhancement measures. An emissions trading program or emission fee that covers as many sources and sinks as possible, combined with regulations where appropriate, could achieve this. National policies can improve cost-effectiveness by providing broader coverage of sources and sinks while reducing adverse competitiveness effects. Use of revenue from auctioned allowances and emissions taxes to reduce existing distortionary taxes can reduce the economic cost of emission reduction policies.

Stimulate development of technologies that lower the cost of emissions reduction, geological storage, and sink enhancement. Policies that encourage research, development, and dissemination of a portfolio of technologies combined with policies to reduce emissions and enhance sinks to create a “market pull” tend to be more effective than either type of policy alone.

Adopt appropriate regulations to complement the emissions trading program or emission fee for sources or actions subject to market imperfections, such as energy-efficiency measures and co-generation. In some situations, credit trading can improve the efficiency of efficiency regulations.

Revise existing policies at the national, state/provincial, and local level with other objectives that lead to higher CO₂ or CH₄ emissions so that the objectives, if still relevant, are achieved with lower emissions.

Implementation of such policies is best achieved by national governments with international cooperation. This provides maximum coverage of CO₂ and CH₄ emissions and carbon sinks. It also allows better allocation of resources for technology research and development. However, constitutional jurisdiction over emissions sources or carbon sinks may reside with state/provincial governments. In that case national policies may need to be coordinated with state/provincial governments, or state/provincial governments may implement coordinated policies without the national government.

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A tool commonly used to compare emission reduction and sequestration options is an emission reduction supply curve, such as that shown in the figure. It compiles the emission reduction and sequestration options available for a given jurisdiction at a given time. If the analysis is for a future date, a detailed scenario of future conditions is needed. The estimated emission reduction potential of each option is based on local circumstances at the specified time, taking into account the interaction among options. The options are combined into a curve starting with the most cost-effective and ending with the least cost-effective. For each option, the curve shows the cost per metric ton of CO₂ reduced on the vertical axis and the potential emission reduction, tons of CO₂ per year, on the horizontal axis. The curve can be used to identify the lowest cost options to meet a given emission reduction target, the associated marginal cost (the cost per metric ton of the last measure included), and total cost (the area under the curve).

An emission reduction supply curve is an excellent tool for assessing alternative emission reduction targets. The best options and cost are easy to identify. The effect on the cost of dropping some options is easy to calculate. And the cost impact of having to implement additional measures due to underperformance by some measures is simple to estimate. The drawbacks are that constructing the curve is a complex analytical process and that the curve is out of date almost immediately because fuel prices and the cost or performance of some options change.

The curve shows the estimated unit cost ($/t CO₂e) and annual emission reduction (t CO₂e) for emission reduction and sequestration options for a given region and date arranged in order of increasing unit cost.
When constructed for a future date, such as 2010 or 2020, the precision suggested by the curve is misleading because the future will differ from the assumed scenario. A useful approach in such cases is to group options into cost ranges, such as less than $5 per metric ton of CO₂, $5 to $15 per metric ton of CO₂, etc., ignoring some interaction effects and the impacts of the policy used to implement the option. This still identifies the most cost-effective options. Comparing the emissions reduction target with the emission reduction potential of the options in each group indicates the most economic strategy.

[END OF TEXT BOX]
Table 4.1. Standardized cost estimates [annualized cost in 2004 constant U.S. dollars per metric ton of carbon (t C)]

<table>
<thead>
<tr>
<th>Option/applicable date(s)</th>
<th>Annualized cost (in $2004 U.S.)</th>
<th>Potential range (Mt C yr⁻¹) or % reduction</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U.S. permit trading)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(U.S. permit trading)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CAFÉ standard)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation/2030</td>
<td>$44/t C</td>
<td>74</td>
<td>Greene et al. (2005)</td>
</tr>
<tr>
<td>(Feebate)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest management/2010–2110</td>
<td>$4 to 109/t C</td>
<td>8 to 94</td>
<td></td>
</tr>
<tr>
<td>Biofuels/2010–2110</td>
<td>$109 to 181/t C</td>
<td>123 to 169</td>
<td></td>
</tr>
<tr>
<td>All industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of fugitives</td>
<td>$92 to 180/t C</td>
<td>3%</td>
<td>Hertzog (1999); Martin et al. (2001); Jaccard et al. (2002, 2003a, 2003b); Worrel et al. (2004); DOE (2006)</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>$0 to 180/t C</td>
<td>12% to 20%</td>
<td></td>
</tr>
<tr>
<td>Process change</td>
<td>$92 to 180/t C</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Fuel substitution</td>
<td>$0 to 92/t C</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>CO₂ capture and storage</td>
<td>$180 to 367/t C</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Waste management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of fugitives</td>
<td>$0 to 180/t C</td>
<td>90%</td>
<td>Hertzog (1999), Jaccard et al. (2002)</td>
</tr>
<tr>
<td>CO₂ capture and storage</td>
<td>&gt;$367/t C</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Entire U.S. economy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No trading</td>
<td>$102 to 548/t C</td>
<td>Marginal cost</td>
<td>EMF (2000)</td>
</tr>
<tr>
<td>Annex I trading</td>
<td>$19 to 299/t C</td>
<td>Marginal cost</td>
<td>EMF (2000)</td>
</tr>
<tr>
<td>Global trading</td>
<td>$7 to 164/t C</td>
<td>Marginal cost</td>
<td>EMF (2000)</td>
</tr>
</tbody>
</table>