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

Coordinating Lead Author: Erik Haites[1]

Lead Authors: Ken Caldeira,[2] Patricia Romero Lankao,[3] Adam Rose,[4] and Tom Wilbanks[5]

Contributing Authors: Skip Laitner,[6] Richard Ready,[7] and Roger Sedjo[8]

[1]Margaree Consultants, Inc., [2]Carnegie Institution, [3]Metropolitan Autonomous University—Xochimilco and Institute for the Study of Society and Environment (NCAR), [4]The Pennsylvania State University and the University of Southern California, [5]Oak Ridge National Laboratory, [6]U.S. Environmental Protection Agency, [7]The Pennsylvania State University, [8]Resources for the Future

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KEY FINDINGS

- Options to reduce energy-related CO_2 emissions include improved efficiency, fuel switching (among fossil fuels and non-carbon fuels), and CO_2 capture and storage.
- Most energy use, and hence energy-related CO_2 emissions, involves equipment or facilities with a relatively long life—5 to 50 years. Many options for reducing these CO_2 emissions are most cost-effective, and sometimes only feasible, in new equipment or facilities. This means that cost-effective reduction of energy-related CO_2 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 CO_2 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 tax; (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 tax 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 CO_2 or CH_4 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 CO_2 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 carbon dioxide (CO_2) and methane (CH_4) 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

Energy-Related CO_2 Emissions

Combustion of fossil fuels is the main source of CO_2 emissions, although some CO_2 is also released in non-combustion and natural processes. Most energy use, and hence energy-related CO_2 emissions, involves equipment or facilities with a relatively long life—5 to 50 years. Many options for reducing these CO_2 emissions are most cost-effective, and sometimes only feasible, in new equipment or facilities (Chapters 6 through 9).

To stabilize the atmospheric concentration of CO_2 “would require global anthropogenic CO_2 emissions to drop below 1990 levels . . . and to steadily decrease thereafter” (IPCC, 2001a).[1] That entails a transition to an energy system where the major energy carriers are electricity and hydrogen produced by non-fossil sources or from fossil fuels with capture and geological storage of the CO_2 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.

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[1] The later the date at which global anthropogenic CO_2 emissions drop below 1990 levels, the higher the level at which the CO_2 concentration is stabilized.

Options to reduce energy-related CO_2 emissions can be grouped into a few categories:

- efficiency improvement,
- 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 CO_2 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.[2] Efficiency improvements reduce CO_2 emissions whenever they reduce the use of fossil fuels at any point between production of the fuel and delivery of the desired service.[3] 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.[4] 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).[5]

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.[6] 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 or electricity transmission 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 CO_2 emissions are primarily due to combustion of fossil fuels. Thus, CO_2 emissions can be reduced by switching to a less carbon-intensive fossil fuel or to a non-carbon fuel.

The CO_2 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 and biodiesel, 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, can use wood waste and sawdust as fuel. Ethanol, currently produced mainly from corn, is blended with gasoline and biodiesel is produced from vegetable oils and animal fats. Wood residuals and cellulose materials, such as switch grass, can be utilized both for energy and the production of syngases, which can be used to produce biopetroleum (AF&PA, 2006). The CO_2 emission reduction achieved depends on whether the biomass used is replaced, on the emissions associated with production of the biomass fuel, and the carbon content of the fuel displaced.[7]

Carbon-free energy sources include hydro, wind, solar, biomass, geothermal, and nuclear fission.[8] 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.

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[7] The CO_2 reductions achieved depend on many factors including the inputs used to produce the biomass (fertilizer, irrigation water), whether the land is existing cropland or converted from forests or grasslands, and the management practices used (no-till, conventional till).

Electricity and Hydrogen from Fossil Fuels with CO_2 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 CO_2 emissions from fossil-fired generating units can be captured and injected into a suitable geological formation for long-term storage.

Hydrogen (H_2) is an energy carrier that emits no CO_2 when burned, but may give rise to CO_2 emissions when it is produced (National Academies, 2004). Currently, most hydrogen is produced from fossil fuels in a process that generates CO_2. The CO_2 from this process can be captured and stored in geological formations. Alternatively, hydrogen can be produced from water using electricity, in which case the CO_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_2 emissions to the atmosphere.[9] 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 too safely and cost effectively integrates CO_2 capture and storage into our energy system, so this is mainly a long-term option (IPCC, 2005).

Industrial Processes

The processes used to make cement, lime, and ammonia release CO_2. Because the quantity of CO_2 released is determined by chemical reactions, the process emissions are determined by the output. But, the CO_2 could be captured and stored in geological formations. CO_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_2 emissions are commercially available. Consumption of the carbon anodes during aluminum smelting leads to CO_2 emissions, but good management practices can reduce the emissions. Raw natural gas contains CO_2 that is removed at gas processing plants and could be captured and stored in geological formations.

Methane Emissions

Methane (CH_4) 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

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[8] Reservoirs for hydroelectric generation produce CO_2 and methane emissions, and production of fuel for nuclear reactors generates CO_2 emissions, so such sources are not totally carbon free.

and used as an energy source. Methane emissions also occur during production of coal, oil, and natural gas. Such emissions usually can be flared or collected for use as an energy source.[10] Ruminant animals produce CH_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.

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[11], 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 environmental factors (such as type of trees planted, soil type, climate, and topography) and management practices (such as thinning, fertilization, and pest control). 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.[12] 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.

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[9] Since combustion of biomass releases carbon previously removed from the atmosphere, capture and storage of these emissions results in negative emissions.

[10] Flaring or combustion of methane as an energy source produces CO_2 emissions.

[11] Afforestation is the establishment of forest on land that has been unforested for a long time.

[12] The 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%.

INTEGRATED COMPARISON OF OPTIONS

As is clear from the previous sections, there are many options to reduce emissions of or to sequester CO_2. To help them decide which options to implement, policy makers need to know the magnitude of the potential emission reduction at various costs for each option so they can select the options that are the most cost-effective—have the lowest cost per metric ton of CO_2 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, in addition to the factors previously cited, on other measures, 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. 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.

TEXT BOX on “Emission Reduction Supply Curve” goes here

The estimated cost and emission reduction potential for the principal short-term CO_2 emission reduction and sequestration options are summarized in Table 4-1. All estimates are expressed in 2004

U.S. dollars per metric ton of carbon.[13] The limitations of emission reduction supply curves noted in the text box apply equally to the cost estimates in Table 4-1.

Table 4-1. Standardized cost estimates for short-term CO_2 emission reduction and sequestration options [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.[14] So the estimated scale of 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 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 Chapters 6 through 11, along with some estimates of their impacts 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 an emissions 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 industrialized country trading case for the U.S. economy.

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[13] A metric ton (sometimes written as “tonne”) is 1000 kg, which is 2205 lb or 1.1025 tons.

[14] For example, increasing the scale of tree planting to sequester carbon requires more land. Typically the value of the extra land used rises, so the additional sequestration becomes increasingly costly.

The task of choosing the "best" combination of options may seem daunting given the numerous options, their associated cost ranges and ancillary impacts. This combination will depend on several factors including the emission target, the emitters covered, the compliance period, and the ancillary benefits and costs 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 emissions trading or emissions taxes, that cover a large number of emitters and allow them to use their first-hand knowledge to choose the lowest cost reduction options.[15]

POLICY OPTIONS

Overview

No single technology or approach can achieve a sufficiently large CO_2 emission reduction or sequestration to stabilize the carbon cycle (Hoffert *et al.*, 1998, 2002). 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. The portfolio of short-term options will include greater efficiency in the production and use of energy; expanded use of non-carbon and low-carbon energy technologies; and various changes in forestry, agricultural, and land use practices. Policies will also need to encourage research and development of technologies that can reduce emissions even further in the long term, such as technologies for removing carbon from fossil fuels and sequestering it in geological formations and possibly other approaches, some of which are currently very controversial, such as certain types of "geoengineering."

Because CO_2 has a long atmospheric residence time,[16] immediate action to reduce emissions and increase sequestration allows its atmospheric concentration to be stabilized at a lower level.[17] 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.

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

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[15] Swift (2001) finds that emissions trading programs yield greater environmental and economic benefits than regulations. Several other studies of actual policies (e.g., Ellerman *et al.*, 2000) and proposed policies (e.g., Rose and Oladosu, 2002) have indicated relative cost savings of these incentive-based instruments.

[16] CO_2 has an atmospheric lifetime of 5 to 200 years. A single lifetime can not be defined for CO_2 because of different rates of uptake by different removal processes. (IPCC, 2001a, Table 1, p. 38)

[17] IPCC, 2001a, p. 187.

impacts on CO_2 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 afforestation/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.

General Considerations

Policies to encourage reduction and sequestration of CO_2 emissions could include information programs, voluntary programs, conventional regulation, emissions trading, and emissions taxes (Tietenberg, 2000). Voluntary agreements between industry and governments and information campaigns are politically attractive, raise awareness among stakeholders, and have played a role in the evolution of many national policies, but to date have generally yielded only modest results.[18] While some programs and agreements have reduced emissions, it appears that the majority of voluntary agreements have achieved limited emissions reductions beyond business as usual. (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 emission trading program 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.

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

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[18] Information 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).

where mitigation costs are lower than the tax, but once mitigation costs exceed the tax, they will opt to pay it.

The framework for choosing a policy instrument needs to consider technical, institutional and socioeconomic constraints that affect its implementation, such 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, employment, or other measures of economic well-being. 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.[19] The cost can have competitiveness impacts if some emitters in other jurisdictions are not subject to similar policies. But societal benefits, such as improved public health and reduced environmental damage, may offset 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).[20] 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 (see, e.g., Rose and Oladosu, 2002).[21] A policy that raises revenue (an emissions tax or auctioned allowances) has a lower cost to the

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[19] 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.

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

[21] 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.

economy than a policy that does not, if the revenue is used to reduce existing distortionary taxes[22] 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.[23]

Carbon dioxide 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 but may also be difficult to implement.

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).[24] In some cases, such as refrigerators, standards have been used successfully to drive technology development.

Terrestrial 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

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[22] A distortionary tax is one that changes the relative prices of goods or services. For example, income taxes change the relative returns from work, leisure and savings.

[23] Initially the reduction may be small because demand for gasoline is not very sensitive to price, but over time the tax causes people to adjust their travel patterns and the vehicles they drive thus yielding larger reductions.

carbon uptake. Policies that affect crop choice (support payments, crop insurance, disaster relief) and 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.[25] 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);[26]
- 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 CO_2 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; Grubb *et al*., 2006). Such induced technological change justifies earlier and more stringent emission reduction targets.

Two types of policies are needed to achieve a given cumulative CO_2 reduction or concentration target at least cost. Policies to reduce emissions and increase sequestration are needed to create a market for less

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[24] 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.

[25] There needs to be a buyer for the credits, such as sources subject to CO2 emissions trading program or an offset requirement. Determination of the quantity of credits earned requires resolution of many issues, including the baseline, leakage, and additionally. Projects 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).

[26] Agriculture and forestry credits could be temporary. Temporary credits could be valuable additions to a carbon reduction portfolio.

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 (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.[27]

CONCLUSIONS

Policies to reduce projected CO_2 and CH_4 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 at any given location by natural phenomena or human activities;
- 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 CO_2/CH_4 emissions.

Under a wide range of assumptions, cost-effective policies to reduce atmospheric CO_2 and CH_4 concentrations cost-effectively in the short and long term would

- Encourage adoption of cost-effective emission reduction and sink enhancement measures. An emissions trading program or emissions tax 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.

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[27] 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.

- Adopt appropriate regulations to complement the emissions trading program or emissions tax 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 CO_2 or CH_4 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 CO_2 and CH_4 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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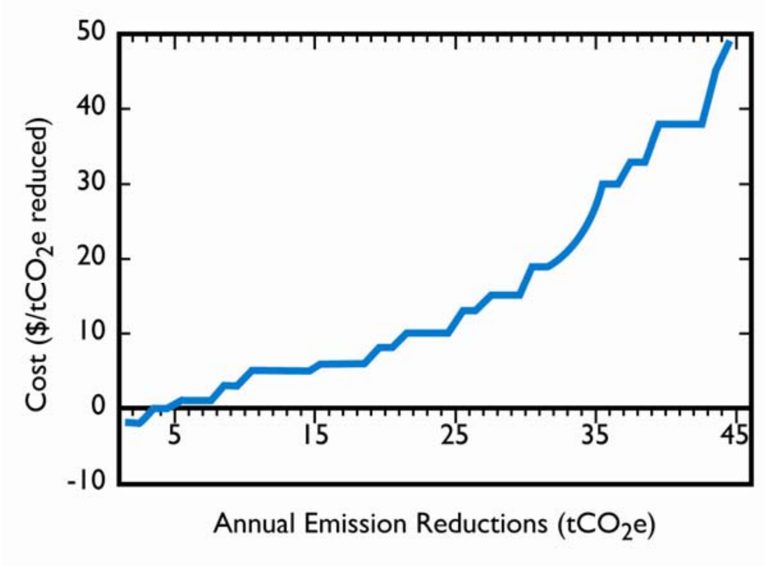
Emission Reduction Supply Curve

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 CO_2 reduced on the vertical axis and the potential emission reduction, tons of CO_2 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 CO_2 equivalent) and annual emission reduction (t CO_2 equivalent) 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 CO_2, $5 to $15 per metric ton of CO_2, 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.

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Table 4.1. Standardized cost estimates for short-term CO_2 emission reduction and sequestration options [annualized cost in 2004 constant U.S. dollars per metric ton of carbon (t C)]

Option/applicable date(s)	Annualized average cost (in $2004 U.S.)	Potential range (Mt C yr^{-1}) or % reduction	Source
Power generation	–$206 to 1067/t C	N.A.	DOE/EIA (2000)
Transportation/2010 (U.S. permit trading)	$76/t C	N.A.	DOE/EIA (2003)
Transportation/2025 (U.S. permit trading)	$214/t C	90	DOE/EIA (2003)
Transportation/2017 (CAFÉ standard)	$74/t C	43	US CBO (2003)
Transportation/2030 (Feebate)	$44/t C	74	Greene *et al*. (2005)
Afforestation/2010–2110	$54 to 109/t C	41 to 247	Lewandrowski (2004), Stavins and Richards (2005), EPA (2005)
Forest management/2010–2110	$4 to 109/t C	8 to 94	
Biofuels/2010–2110	$109 to181/t C	123 to 169	
Agricultural soil carbon sequestration/2010–2110	$4 to 109/t C	19 to 49	EPA (2005)
All industry			
Reduction of fugitives	$92 to 180/t C	3%	Hertzog (1999); Martin *et al*. (2001); Jaccard *et al*. (2002, 2003a, 2003b); Worrel *et al*. (2004); DOE (2006)
Energy efficiency	$0 to 180/t C	12% to 20%	
Process change	$92 to 180/t C	20%	
Fuel substitution	$0 to 92/t C	10%	
CO_2 capture and storage	$180 to 367/t C	30%	
Waste management			
Reduction of fugitives	$0 to 180/t C	90%	Hertzog (1999), Jaccard *et al*. (2002)
CO_2 capture and storage	>$367/t C	30%	
Entire U.S. economy			
No trading	$102 to 548/t C [a]	Not specified	EMF (2000)
Industrialized country trading	$19 to 299/t C [a]	Not specified	EMF (2000)
Global trading	$7 to 164/t C [a]	Not specified	EMF (2000)

Sources: Chapters 6–10 of this report.

[a] Annualized marginal cost (cost at upper limit of application, and therefore typically higher than average cost).

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