# Greenhouse Gas Mitigation Options For Washington State

Prepared for: Environmental Protection Agency

Prepared By: Nicolas Garcia

Washington State Energy Office
925 Plum Street SE
PO Box 43165
Olympia, WA 98504-3165

This report can be made available in another format for people with disabilities. Please call (360) 956-2068. TDD users call (360) 956-2218.
April 1996
WSEO #96-28

Printed on recycled paper

WSEO
Washington State Energy Office

## Acknowledgments

The author wishes to thank the Environmental Protection Agency, Office of Policy, Planning and Evaluation for their financial contribution to this effort. Special thanks go to Katherine Sibold, the Director of State Outreach Programs, for her help and patience.

The author wishes to thank all the staff of the Washington State Energy Office for their help and insights regarding ways to improve energy efficiency. Thanks also go to those who reviewed early drafts of this report, especially Jim Kerstetter for his scientific insights and Patti Lowe for her persistence and support for this project. Finally, thanks to Sarah Beckham for the final preparation of the report.

## Disclaimer

…people can not imagine geologic time. Human life is lived on another time scale entirely. An apple turns brown in a few minutes. Silverware turns black in a few days. A compost heap decays in a season. A child grows up in a decade. None of these everyday experiences prepares people to be able to imagine the meaning of eighty million years…

—Michael Crichton, Jurassic Park

…*Does a climate exist?* That is, does the earth's weather have a long term average? Most meteorologists...took the answer for granted. Surely any measurable behavior, no matter how it fluctuates, must have an average. Yet on reflection, it is far from obvious. As [Edward] Lorenz pointed out, the average weather for the last 12,000 years has been notably different than the average for the previous 12,000, when most of North America was covered by ice. Was there one climate that changed to another for some physical reason? Or is there an even longer-term climate within which those periods were just fluctuations? Or is it possible that a system like the weather may never converge to an average?

—James Gleick, CHAOS Making a New Science

# Author's Note

Writing about global warming is a difficult task for many reasons. First, the science is rapidly evolving and with it our understanding of the world's climate system. During the writing of this report, it seemed that every few days new estimates would emerge on temperature changes, storm intensities, spatial ranges of diseases, or changes in agriculture yields and forestry production. In this situation, one difficulty lies in the decision to stop researching and start writing. Certainly, some aspects of this report were out of date even before it was completed.

A second difficulty lies in the enormous scope of the science. Global climate change could potentially affect virtually all aspects of human society and the environment. As such, a vast and growing climate change library covers everything from changes in water resources to the prevalence of extreme weather events to the comparative advantage of various species of subterranean biota. For the most part, information included in the report came from peer reviewed articles, government reports and books published after 1990. I reviewed several hundred potential information sources -- more than 100 of which made their way into the report as references. Nevertheless, this number constitutes only a small proportion of the information available on climate change. Inevitably, reports containing important information on climate change were overlooked.

A final difficulty is the often conflicting conclusions of scientists regarding the consequences of climate change. For example, Rosenzweig reports optimistic prospects for agriculture )at least in the developed world) under global climate change while Bazzaz appears rather less sanguine. Such conflicting reports allow for many different assessments regarding the consequences of climate change. My reading of the scientific record could not support a conclusion that suggests that climate change poses a substantial threat to Washington state over the next 80 to 100 years. Indeed, to my mind, the consequences appear significant but relatively small in magnitude. However, other interpretations of the record are equally valid as are other conclusions regarding the threat to this State posed by climate change.

# EXECUTIVE SUMMARY

President Clinton, in 1993, established a goal for the United States to return emissions of greenhouse gases to 1990 levels by the year 2000. One effort established to help meet this goal was a three part Environmental Protection Agency state grant program. Washington State completed part one of this program with the release of the 1990 greenhouse gas emissions inventory and 2010 projected inventory.[1] This document completes part two by detailing alternative greenhouse gas mitigation options. In part three of the program EPA, working in partnership with the States, may help fund innovative greenhouse gas reduction strategies.

The greenhouse gas control options analyzed in this report have a wide range of greenhouse gas reductions, costs, and implementation requirements. In order to select and implement a prudent mix of control strategies, policy makers need to have some notion of the potential change in climate, the consequences of that change and the uncertainties contained therein. By understanding the risks of climate change, policy makers can better balance the use of scarce public resources for concerns that are immediate and present against those that affect future generations. Therefore, prior to analyzing alternative greenhouse gas control measures, this report briefly describes the phenomenon and uncertainties of global climate change, and then projects the likely consequences for Washington state.[2]

Global climate change poses daunting public policy problems. According to some the consequences will be nothing short of apocalyptic: world wide famine, epidemics, massive flooding, and more violent storms. To others, the consequences are minimal and perhaps even beneficial in specific areas like agriculture. The divergence of opinions reveals the limitations in our understanding of the global environment and climate system. Scientists agree that continued consumption of fossil fuels will elevate greenhouse gas levels in the atmosphere. Most also agree that higher greenhouse gas concentrations will raise average global temperatures—though they debate its magnitude and timing. This agreement breaks down when predicting secondary effects like precipitation, soil moisture, storm severity and flooding. A limited understanding about how flora and fauna may respond to climate change further compounds the uncertainty. Despite these uncertainties, policy makers need to know the potential threats and uncertainties posed by climate change if they are to develop well reasoned policy responses.

Based on work by the Intergovernmental Panel on Climate Change, this report assumes that doubling pre-industrial levels of atmosphere greenhouse gases (somewhere between the years 2060 and 2090) will raise temperatures in Washington by 2°C (about 4°F) and will not change average precipitation levels. This report analyzes the Human Health, Agriculture, Forestry, Fisheries, Power Production, Sea-Level Rise and Economic effects of such changes. With the exception of sea-level rise, the consequences of the presumed climate changes appear relatively

---

[1] Greenhouse Gas Emissions Inventory For Washington State, 1990, Washington State Energy Office, 1994 (WSEO #93-260) and Projected Greenhouse Gas Emissions Inventory For Washington State in 2010, Washington State Energy Office, 1994 (WSEO #94-193).

[2] This report acknowledges that by its very nature global warming is a world issue. However, the contract with EPA was to evaluate mitigation measures available in Washington State. (So, for example, expenditures by Washington to reduce greenhouse gases in other parts of the world were not considered.) Therefore, it seemed reasonable to contemplate what our mitigation efforts would protect Washingtonians against. The effects of climate change in other parts of the world could be more or less severe than projected for Washington. This approach reveals who—Washington residents or others—benefits from our mitigation efforts.

mild in Washington. However, one important limitation of this report is that each area (e.g., human health) was analyzed independently. Interactions between areas could result in outcomes significantly different than predicted here. Moreover, atmospheric greenhouse gas levels will grow beyond twice pre-industrial levels. Thus, the consequences for Washington could be greater further in the future.

It is important to remember that our understanding of the global climate system is limited. Thus, the projected consequences of climate change are speculative and will change as we learn more about the global climate system. For example, estimates of sea-level rise have gone from 10

### *Projected Consequences of Climate Change*

Health Effects: A 2°C temperature change will not likely have severe adverse affects on the health of Washington citizens (the temperature extremes would still be well below those presently occurring in other areas of the country). Further, a 2°C temperature change is not likely to bring important tropical diseases to Washington.

Agricultural: Agriculture may actually benefit from the climate change. The primary greenhouse gas, carbon dioxide, is an essential plant nutrient. A 2°C temperature rise may expand the growing season and is well within the tolerance limits of most cash crops. EPA reports that agriculture acreage in the Pacific Northwest could increase 5 to 17 percent as a result of climate change. However, irrigation requirements may also increase.

Forestry: Climate change may alter the comparative advantages between tree species and thus change the climax species of an area. Forests may expand into some currently inhospitable environs and withdraw from others. However, since trees are long-lived, these shifts may not be noticeable for many years. The carbon dioxide fertilization effect may somewhat mollify the effects of climate change. The risk of forest fires will also increase with climate change. Warmer temperatures would dry out forests, lengthen the fire season and increase both the area burnt and number of forest fires.

Fish: Climate change will likely affect fish resources through changing rainfall/snow melt patterns. One study of 60 Pacific northwest salmonoid subspecies found climate change to adversely affect 14 species, to not affect 24 species and to benefit 21 species. However, given the critical condition of many fish species climate change may ultimately introduce more stress on fish stocks already depleted due to other environmental factors.

Energy: Energy production in the Pacific Northwest is vulnerable to climate change due to our heavy reliance on hydroelectric power. With constant precipitation and a lower snow pack volume (from warmer temperatures) winter and spring river flow will increase. Earlier spring runoff may ease supply constraints during the period of highest demand. Conversely, lower summer and fall flow would degrade water supply reliability. Warmer temperatures will lessen wintertime demand for heating but increase summertime cooling demand.

Sea-Level Rise: Climate change is estimated to raise sea-levels by about 1.3 feet through 2100. Motions of the earth's crust complicate the effect of sea-level rise. Washington's coast is currently rising relative to the ocean. Uplift should roughly equal the projected sea-level rise along northern and southern coasts. Over the mid-coastal area, the sea level may rise a foot or more. Along inland waters the sea level may rise 1 foot in the northern Puget Sound and 1.5 feet in south Puget Sound.

Economy: The effects of climate change on Washington's economy do not appear significant. The economic sectors that are potentially most affected by climate change—agriculture, forestry and fisheries—account for about 8 percent of the state's economy. And agriculture and forestry may actually do better under climate change. Moreover, continued expansion of the service sector should lower the portion of the economy at risk to climate change. However, exports are an important part of Washington's economy. Climate change could reduce the foreign customers ability to purchase Washington state goods and services.

meters to less than one meter. In addition, surprises—good and bad effects beyond our ability to predict with current knowledge—are possible (or even probable) as climate, environments, and species interact and adapt in unexpected ways. Beyond these considerations are uncertainties about the rate carbon dioxide is added to the atmosphere. Advances in combustion turbine technology, for example, have lowered carbon dioxide emissions per unit of electricity produced by 70 percent relative to traditional coal fired power plants. The Administration also is sponsoring a research effort to triple the fuel efficiency of motor vehicles. The success and application of such efficiency technologies (or lack thereof) will have a huge effect on the magnitude and timing of climate change. Thus, the reported climate change projections and the consequences thereof may reasonably describe what will occur or may be completely wrong.

Uncertainties about the consequences of climate change create a dilemma. Years to decades will pass before uncertainties about climate change are resolved. Waiting risks irreversible damages while immediate action risks large expenditures to mitigate inconsequential or even beneficial changes. There are several ways policy makers might approach this balancing effort. One is to consider greenhouse gas mitigation measures as insurance against uncertain risks. Following this logic results in an active greenhouse gas control program to reduce our risks until knowledge about climate change improves. Another approach is to invest heavily into research and development in technologies with the potential to reduce greenhouse gas emissions. A third approach is to implement only those activities that make sense for reasons beyond climate change—a “no regrets” approach. Determining the appropriate government response to climate change requires the skills of both scientists and policy makers; scientists to describe potential consequences and policy analysis to balance the potential threats and opportunities of climate change against other social needs and desires.

For Washington to stabilizing greenhouse gas emissions—President Clinton’s goal—requires an 18 million ton reduction from “business as usual” in the year 2010. The transportation category emits the most carbon dioxide and therefore is the largest emission reduction target. Industrial and utilities are the next two emission categories followed by the residential and commercial sectors. No single activity in Washington dominates carbon dioxide emissions, and therefore, no single measure can stabilize this state’s greenhouse gases. Significant reductions in greenhouse gas emissions will require a broad range of mitigation programs.

Table 1 lists the mitigation strategies evaluated in this report that cost less than $100 per ton of greenhouse gas controlled. The reduction and costs estimates required many assumptions about society in the year 2010. Small errors compounded over time (e.g., fuel consumption patterns), or large errors in technology assessment (e.g., the introduction of residential fuel cells) could easily upset these figures. Nonetheless, the estimates are reasonable given what we know today. About three-fourths of the carbon dioxide reductions necessary to achieve the President's goal have low costs. "No regrets" options could reduce emissions by 8 million tons. They include upgrades to building codes and efforts to alter building operating practices. Measures costing less than $5 per ton reduce emissions another 5.6 million tons, principally through afforestation. Further reductions are more expensive. A $1.00 per gallon gasoline tax, for example, could eliminate 8.5 million tons of carbon dioxide at a cost of about $15 per ton.

**Table 1**

## Alternative Greenhouse Gas Mitigation Strategies†

| Strategy | Potential Annual Emission Reductions in 2010 (Tons) | Cost per Ton Reduced |
|---|---|---|
| ***Residential Sector*** | | |
| EXISTING HOME RETROFITS | | |
| Direct Use of Natural Gas in Buildings | 250,000 | + |
| R-19 Attic for Electrically Heated Homes | 209,000 | + |
| R-11 Wall for Homes | 113,000 | + |
| R-19 Floor for N.G. Heated Homes | 105,000 | + |
| R-30 Attic for N.G. Heated Homes | 15,000 | + |
| Low Flow Shower Head | 7,000 | + |
| Hot Water Tank Upgrade (N.G.) | 4,000 | $3 |
| R-11 Duct Insulation For N.G. Homes | 11,000 | $16 |
| Caulking Joints in N.G. Homes | 5,000 | $33 |
| Install Fluorescent Lighting in Buildings | 460,000 | ? |
| NEW HOME BUILDING PRACTICES | | |
| Class 35 Windows Code | 106,000 | + |
| R-30 Floor Code for N.G. Homes (Zone 1) | 17,000 | $59 |
| R-38 Attic Code for N.G. Homes (Zone 1) | 6,000 | $74 |
| R-21 Walls Code | 25,000 | $78 |
| ***Commercial Sector*** | | |
| Efficient Fluorescent Lighting Retrofits | 5,400,000 | + |
| More Efficient Food Refrigeration | 550,000 | + |
| A variety of Efficiency Improvements for Public Sector Commercial Buildings | 438,000 | + |
| ***Industrial Sector*** | | |
| Petroleum Refining Process Improvements | 134,000 | ? |
| Pulp and Paper Process Improvements | 1,049,000 | ? |
| Aluminum Process Improvements | 1,184,000 | ? |
| ***Transportation Sector*** | | |
| Tire Pressure Check | 35,000 | + |
| More Efficient Airplane Engines | 800,000 | + |
| FeeBate ($100/MPG off baseline) | 4,400,000 | ~$0 |
| Gas Tax ($1.00/gallon) | 8,500,000 | $15 |
| Vehicle Mileage Tax ($0.04/mile) | 8,200,000 | $45 |
| Parking Restrictions | ? | $? |
| Diesel to Electric Train Conversion | 220,000 | $? |
| Truck to Train Mode Shift | 1,680,000 | $? |
| ***Generating Resources*** | | |
| Chemical Boiler Cogeneration | 410,000 | + |
| Landfill Gas Combustion | 494,000 | ~$0 |
| Animal Manure | 110,000 | $2 |
| Nuclear Power (extend WNP-2) | 2,960,000 | $25 |
| Wood Waste Combustion | 150,000 | $80 |
| Agricultural Waste Combustion | 282,000 | $93 |
| Wind | 450,000 | ? |
| ***Carbon Sequestration*** | | |
| Afforestation | 5,500,000 | $4 |

† The cost per ton based on carbon dioxide equivalent reductions. (See Global Warming Index sidebar.)
A "+" indicates a net benefit—the efficiency measure's costs are completely offset by reduced energy expenditures.
A "?" denotes uncertain costs. The reduction estimates are not additive (e.g., interactions between strategies may result in an over estimate of the actual result if added together). Moreover, the number of alternatives reviewed prevented detailed review of individual programs. Therefore, the numbers presented above are preliminary. See the body of the report for a more detailed explanation of each mitigation strategy, and its associated emission reduction and cost.

# TABLE OF CONTENTS

# INTRODUCTION

Global climate change poses daunting public policy problems. Since humans first effectively harnessed the energy within coal and oil, a myriad of new technologies and machinery have saved inestimable amounts of labor and vastly improved living standards. We dwell and work in large homes and buildings which are warm in the winter and cool in the summer, we routinely travel great distances and we have access to a wide array of consumer goods. And yet the principal power source supporting this living standard may threaten the world community. Fossil fuels emit carbon dioxide when burned. Over the past 100 years, carbon dioxide levels in the atmosphere increased 25 percent. Carbon dioxide concentrations will continue to increase as the world population grows and societies around the globe industrialize.

Within the scientific community there is near unanimity of opinion that adding carbon dioxide and other greenhouse gases to the atmosphere will alter the Earth's climate. The great debate and uncertainty is over how much and how rapidly the climate will change, and how that change will affect flora, fauna, and human society. Depending upon the speaker, the projected effects of climate change range from apocalyptic to desirable. The divergence of opinions reveals our limited knowledge and understanding of how the climate system works. Even more uncertain are regional changes in important climate parameters like temperature, soil moisture, precipitation, storm severity and flooding. Understanding how climate change might affect these parameters is extremely important as flora, fauna and human society are sensitive to them all.

Compounding the scientific uncertainties are the economic costs of greenhouse gas mitigation programs. Estimates of the cost of stabilizing greenhouse gas emissions at 80 percent of their 1990 levels range from essentially no cost up to a permanent and re-occurring 3 percent loss in U.S. Gross National Product. The uncertain consequences of climate change along with potentially high mitigation costs makes developing and implementing an appropriate response extremely difficult. Oates and Portney summarize the scientific and policy difficulties associated with global climate change as follows:

> *It is hard to imagine a policy problem more daunting than global warming. To begin with, we are not sure what we are up against. The problem is shrouded in uncertainties of the most difficult sort. Actions today to reduce emissions of greenhouse gases will have their effects on global climate many years down the road, and the magnitude and timing of these effects are the subject of much dispute. Point estimates of possible changes in temperature, rainfall, and other dimensions of global climate come with large confidence intervals, and the estimates are themselves often based on relatively simplistic extrapolations that do not allow for potentially frightening changes in climate should we set off processes of which we are currently unaware. Our imperfect knowledge has led to sharply contrasting policy positions: at one extreme are those suggesting that we wait until we have a firmer understanding of the global warming process before adopting costly preventive measures; at the other are those urging rapid action to forestall some possibly catastrophic outcomes.*
>
> *But uncertainty is not the only aspect of global warming that makes it so difficult to address. Effective policies to reduce emissions of greenhouse gases are likely to be very expensive. William Nordhaus [1991], for example, estimates that the cost of cutting greenhouse gas emissions in half, if done efficiently on a worldwide scale, would be on the order of 1 percent of world output, and could easily cost more. We could find ourselves in the United States spending as much on such policies as we spend on all other efforts to control pollution combined! Moreover, global warming is an international public good. Emissions*

*from one country are essentially a perfect substitute for emissions elsewhere. The issue then is one of total planetary emissions of these gases. And no one country is of sufficient size to "go it alone." Effective policies to address global warming will have to be international in scope--they must enlist widespread participation if there is to be any hope of success.*

*--Bill Oates and Paul Portney*

Climate change is disquieting precisely because of what we do not know: its magnitude, timing and the range of consequences. Further, present day decision-makers will be long dead before the consequences are known. The scientific uncertainties and mitigation costs leave policy makers with a conundrum. On the one hand, failure to act may hasten the onset of severe climate effects. On the other hand, an investment of vast resources may prevent an insignificant or even beneficial climate change. As such, policy makers need the wisdom of Solomon to devise a response that balances present day economic growth and prosperity with the future environment. While this report makes no claim to impart such wisdom, it should provide policy makers with some notion of the key uncertainties of climate change, the potential effects in Washington state and the measures available to lower greenhouse gas emissions. Policy makers need such information to balance present day social and economic needs with the potential harm caused by climate change to future generations and the environment.

To this end, this report begins with a description of current knowledge and key uncertainties about the greenhouse effect. This section includes a discussion of the magnitude and timing of anticipated changes in important climate parameters. This section then speculates about the effect of these climate changes on Washington State. The second section of this report projects the State's greenhouse gas emissions inventory for the years 1990 and 2010. Next is a description of various options available to reduce emissions of greenhouse gases. Whenever possible, estimates of the carbon dioxide reduction potential and economic costs of each option are included. The report concludes with a discussion of alternative approaches policy makers might follow to develop a response to global climate change.

# THE GREENHOUSE EFFECT

All celestial bodies radiate energy. The wavelength of the radiated energy is inversely related to the temperature of the celestial body. The hot sun emits short wavelength radiation that easily passes through the Earth's atmosphere. The relatively cool Earth radiates long wavelength infrared energy. Atmospheric gases such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone can "intercept" some of this infrared energy and re-radiate it in all directions. The portion directed downwards further warms the Earth. This phenomenon, known as the greenhouse effect is a vital part of Earth's climate. The earth would be some 30 degrees Celsius colder were greenhouse gases absent from the atmosphere.

Climate change has become a concern because of increasing levels of greenhouse gases in the atmosphere. Over the last 100 years fossil fuel consumption (e.g., the burning of coal, petroleum products and natural gas), deforestation and

***The Radiation Budget***

The radiative budget is a term used by scientists to track energy flows in the atmosphere. It basically works as follows: Incoming solar radiation has an energy of 340 Watts per square meter ($W/m^2$) of which 100 $W/m^2$ is reflected back into space (from ice, snow and clouds). The remaining 240 $W/m^2$ warms the earth to -18°C. The earth's surface radiates 420 $W/m^2$. The atmosphere absorbs a large fraction of the of the 420 $W/m^2$ and re-radiates 180 $W/m^2$ back to earth. This raises the Earth's temperature to about 15° C. Doubling pre-industrial atmospheric carbon dioxide ($CO_2$) levels would increase the energy reflected back to earth by about 4 $W/m^2$. However, while it is relatively easy to predict how atmospheric changes affect the radiation budget, estimating a temperature and climate response is much more difficult.

industrial activity has elevated carbon dioxide levels from 280 to 350 parts per million; methane concentrations from 0.8 to 1.7 parts per million; and nitrous oxide levels from 288 to 310 parts per billion. These additional greenhouse gases portend a stronger greenhouse effect and a warmer earth. In fact, the Intergovernmental Panel on Climate Change (IPCC, 1992) concluded that the global mean temperature has increased 0.3 to 0.5°C since the 1880s.[3]

Attributing this rise in temperature to a specific cause is very difficult. Scientists predict the effect of increased greenhouse gas concentrations on the global climate with computer global circulation models (GCMs). While scientists are improving the physical realism of these models, shortcomings remain. Perhaps most important is that several important climate feedbacks are only partially understood. For example, alone, a doubling of carbon dioxide levels would raise temperatures less than 1°C. GCMs presume that a carbon dioxide induced temperature rise will increase atmospheric water vapor—a potent greenhouse gas—and magnify the climate change. However, the magnitude of the water vapor and other feedbacks is the subject of much scientific debate and active research. (See sidebar). Despite this and other shortcomings, GCMs do represent the global climate system reasonably well and in any case are the best predictive tool available.

Furthermore, knowledge about how the climate system works continues to grow. For example, chlorofluorocarbon gases were once thought significant greenhouse gases (a 0.6 $W/m^2$ increase in radiative-forcing) but are now assumed to have no <u>net</u> effect. Though potent greenhouse gases, they destroy stratospheric ozone, another global warming gas. The decrease in global warming potential from stratospheric ozone depletion is thought to offset the radiative-forcing contribution of chlorofluorocarbons. Therefore, GCM predictions that include the radiative forcing of chloroflourocarbons systematically overstate warming.[4]

***Climate Feedbacks***

A climate feedback is any mechanism that amplifies or diminishes the effect of the original change in the system. In addition to water vapor, other important climate feedbacks include:

- <u>Snow-Ice Albedo</u>: Snow and ice reflect light (albedo) and lower temperatures. Warming induced ice/snow recession would decrease light reflection and intensify warming. If, however, climate change increases polar precipitation (as some GCMs project) snow/ice at the poles may expand, reflect more light and slow warming.
- <u>Cloud</u>: The cloud feedback is large, complex and poorly understood. Clouds are though to have a net cooling effect, depending on latitude and water content If cloud formation increases with global warming (due to increased evaporation) a cooling feedback may occur.
- <u>Ocean</u>: Ocean storage of $CO_2$, depends on temperature and physical behavior (ocean currents). Ocean feedback is usually thought to accelerate global warming, however, regional responses are poorly understood.
- <u>Methane:</u> Warmer temperatures speed the chemical transformation of methane into less potent $CO_2$ Warming may also increase methane releases from oceans. The resulting feedback from these opposing effects is uncertain.

---

[3] The IPCC, a joint effort of the United Nations Environmental Programme and the World Meteorological Organization , was formed in 1988 to assess the current scientific information on climate change. One degree Celsius is equivalent to 1.8 degrees Fahrenheit. Therefore, the temperature rise ranges from 0.5 to 0.9°F.

[4] By lowering stratospheric ozone levels and allowing more ultraviolet radiation to reach the earth's surface, chlorofluorocarbons may initiate another cooling effect. Ultraviolet radiation produces hydroxyl radicals, highly reactive molecules. (Hydroxyl radicals consists of one oxygen and one hydrogen atom). Hydroxyl radicals have two cooling effects: they scavenge methane from the atmosphere (another greenhouse gas) and through a complex interaction with sulfur dioxide they may increase cloud albedo (Toumi, Bekki).

On the other hand, Daniel et. al., warns that many chlorofluorocarbon substitutes are *"effective radiative absorbers but lead to zero or very little ozone loss, making them very effective net warming agents… [T]he nature and magnitude of substitutes west for current [chlorofluorocarbon] sources is likely to become a subject of increasing importance in predicting future climate change."* This could result in sharply increased "*halocarbon radiative heating in the latter part of the 21st century.*"

A second example of improved understanding about the climate system concerns the cooling effects of sulfur dioxide pollution. Once in the atmosphere, sulfur dioxide transforms into sulfate aerosols. These aerosols intercept some sunlight before it reaches the earth and reflect it back into space. The cooling effect of sulfate aerosols may reach 1 $W/m^2$ (Charlson). Efforts to control sulfur dioxide emissions will lower the cooling effect of this pollutant.[5]

After considering these and other developments, the IPCC recently concluded that recent changes in global temperature were *"…unlikely to be entirely due to natural causes and that a pattern of climatic response to human activities is identifiable in the climatological record."* (IPCC, 1995). As this IPCC conclusion indicates, little debate remains over the physics of global warming. Most agree that elevated greenhouse gas levels will raise temperatures and alter the climate.[6] However, projecting the magnitude and timing of the change is very complicated. A basic element of this projection is the rate at which greenhouse gas concentrations increase. The four GCMs presented in the 1992 IPCC supplemental report model a doubling of greenhouse gas concentrations in 70, 60, 100 and 170 years. This is a heroic assumption since scientists cannot even balance the present day carbon cycle. After subtracting ocean uptake and atmospheric loading from fossil fuel and terrestrial emissions, some 1.2 metric gigatons (approximately 1.4 billion short tons) of carbon dioxide remain unaccounted for (Tans, Douglas). Some recent research suggests that a combination of uptake by Northern Hemisphere forests and carbon deposition account for the missing carbon (Schimel, Culotta).

**_Computer Climate Model Limitations_**

Computer climate models are derived from weather-forecasting programs. They have many built-in assumptions based on past weather and climate. Fundamentally different conditions, like elevated $CO_2$ levels, may invalidate those assumptions.

Computer power also limits GCMs. As such they simplisticly represent climate. For example, many hold that the oceans drive much of world climate (Rahmstorf). Unfortunately, both our understanding of ocean behavior and GCM modeling of atmosphere/ocean interaction are wanting. Climate models also do not deal well with chaotic behavior; unexpected variations in wind/ocean behavior can significantly alter climate predictions.

Another difficulty in predicting long-term climate change is fluctuations in atmospheric carbon dioxide loading. Most GCMs assume a linear or exponential increase in greenhouse gas levels. However, actual loading is very much more variable. Conway et. al., report that carbon dioxide loading fell from almost 5 gigatons per year to less than 2 gigatons per year between 1987 and 1992. (This indicates the variability of atmospheric carbon loading; it does not signify a downward trend.) Francey et. al. attributes much of the recent change to a strong El Niño event.[7]

---

[5] Efforts to control sulfur dioxide pollution has two adverse global warming effects: fewer aerosols will be present to reflect incoming solar radiation and control equipment often decreases power plant efficiency, raising carbon dioxide emissions per unit energy produced. While sulfur dioxide emissions have clearly fallen in the U.S., world wide trends are less clear. For example, should high sulfur coal partially power industrialization in China, overall emissions could increase.

[6] Some do dispute the IPCC conclusion. Dissenters observe that: 1) the recent warming mostly occurred between 1880 and 1940, a period of slowly rising greenhouse gas levels and a response too quick to account for the ocean's thermal lag; 2) the geographic distribution of warming, primarily in the tropics, is not consistent with GCM predictions; 3) GCMs project warming and cooling periods of up to 0.5°C even when the radiation forcing is held constant; and 4) the warming may be a natural recovery from the little ice age of 1300 to 1800. Solow argues that "[w]hen natural variability is so great, it is dangerous to attribute any particular change to any particular cause."

[7] During El Niño events ocean upwelling along the western South American coast is minimized and carbon-poor ocean waters increase uptake of carbon dioxide. La Niña events, the converse of El Niño events, lower equatorial sea-surface temperatures and encourage the upwelling of carbon rich waters, releasing carbon dioxide to the atmosphere. Presently, scientists do not know the cause of El Niño or La Niña events.

The amount of carbon dioxide added to the atmosphere also depends on carbon cycle feedbacks. Temperature, precipitation, vegetation distribution, land use and atmospheric carbon dioxide levels all affect terrestrial systems carbon uptake. Secondary factors include increased ultraviolet radiation, eutrophication, and pollution on terrestrial and aquatic ecosystems. Francey reports that ocean and terrestrial uptake can each annually vary up to 2 gigatons of carbon dioxide. Presently, our understanding of the implications of carbon cycle feedbacks is lacking (Chameides). Therefore, while it is generally agreed that greenhouse gas levels will rise over time, considerable uncertainty remains as to how quickly this will occur.[8]

Finally, it is important to remember that regional climate changes can vary significantly from global averages. Moreover, seasonal changes in precipitation, soil moisture, sea level and storm severity are likely to be very important consequences of climate change. As a result, uncertainties abound when predicting the consequence of climate change for a region.

## THE EFFECTS OF GLOBAL WARMING IN WASHINGTON STATE

Prior to discussing the potential effects of global climate change on the Pacific northwest, we examine changes in temperature and precipitation in Washington since 1900. Figure 1 reveals that temperatures across the state increased through the 1930s and, despite substantial year-to-year variation, held steady on average thereafter.[9] (There does, however, appear to be an increase in minimum temperatures since the 1950s.) In western Washington, average annual temperature typically varies about 0.5°C between years and changes over 1.0°C are not uncommon. Eastern Washington experiences higher inter-annual variation; averaging 0.7°C and ranging up to 1.5°C. This figure does not indicate whether changes in seasonal temperatures occurred.

Figure 2 presents precipitation levels across Washington. Although quite variable, rainfall appears to have changed little over the past 90 years. However, between years rainfall changes average more than 15 percent (both increasing and decreasing) and changes over 35 percent have occurred. Together, the temperature and precipitation profiles in Washington indicate a climate prone to relatively large swings in character. The effects of global climate change must be considered against this natural variability.

[8] As our knowledge about the global climate system is incorporated into the GCMs, projections about the timing and magnitude of climate change will evolve. For example, the 1990 IPCC report projects global temperatures rising 1.5 to 4.5°C in response to a doubling of effective carbon dioxide levels. The Draft 1995 IPCC report amends that projection to 0.8-3.5°C. A "best guess" equilibrium temperature rise through the year 2100 from projected concentrations of greenhouse gases ranges from 1.4 to 2.8°C. However, this is only 50-70% of the ultimate temperature rise expected from carbon dioxide levels anticipated for the year 2100.

Moreover, there is no reason to believe greenhouse gases concentrations will stabilize by the year 2100. One must view the temperature estimates as points along the global warming path. On the other hand, Cline suggests that over the long-term (250+ years), deep ocean mixing will increase ocean carbon dioxide uptake, partially reversing the atmospheric build-up.

[9] Information on Washington state temperature and precipitation came from Trends '93, A Compendium of Data on Global Change, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratories. The data divided the state into three sections: North Pacific Coast; North Cascades; and East Slope North Cascades (see figure at right)..

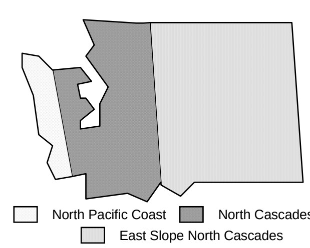


**Figure 1**

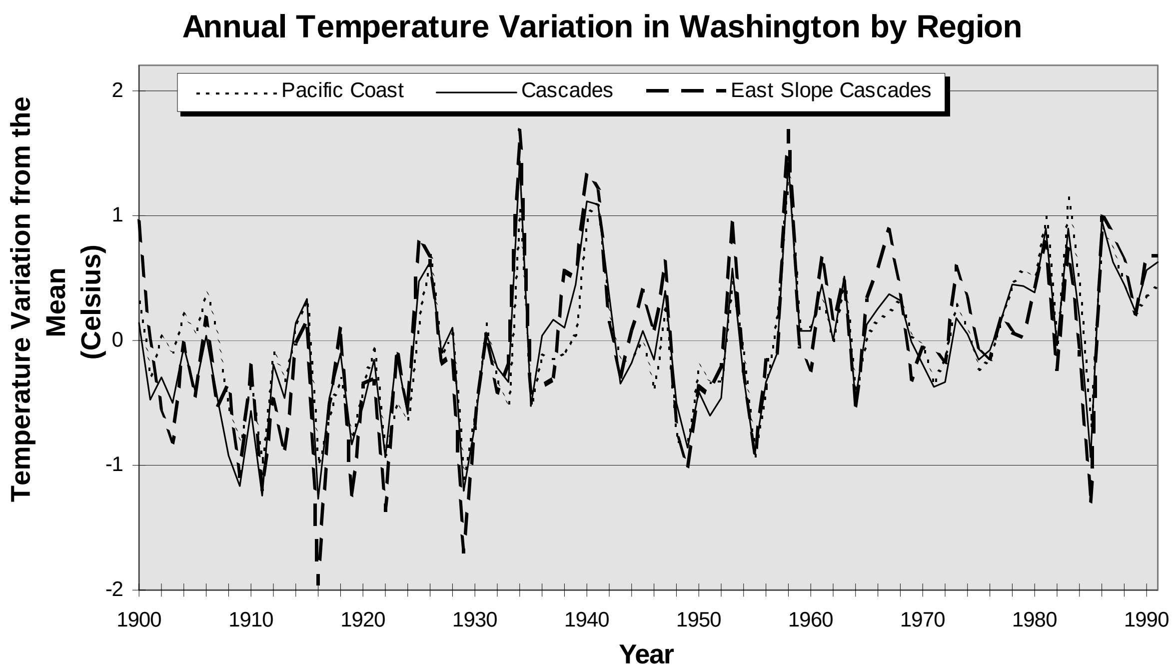
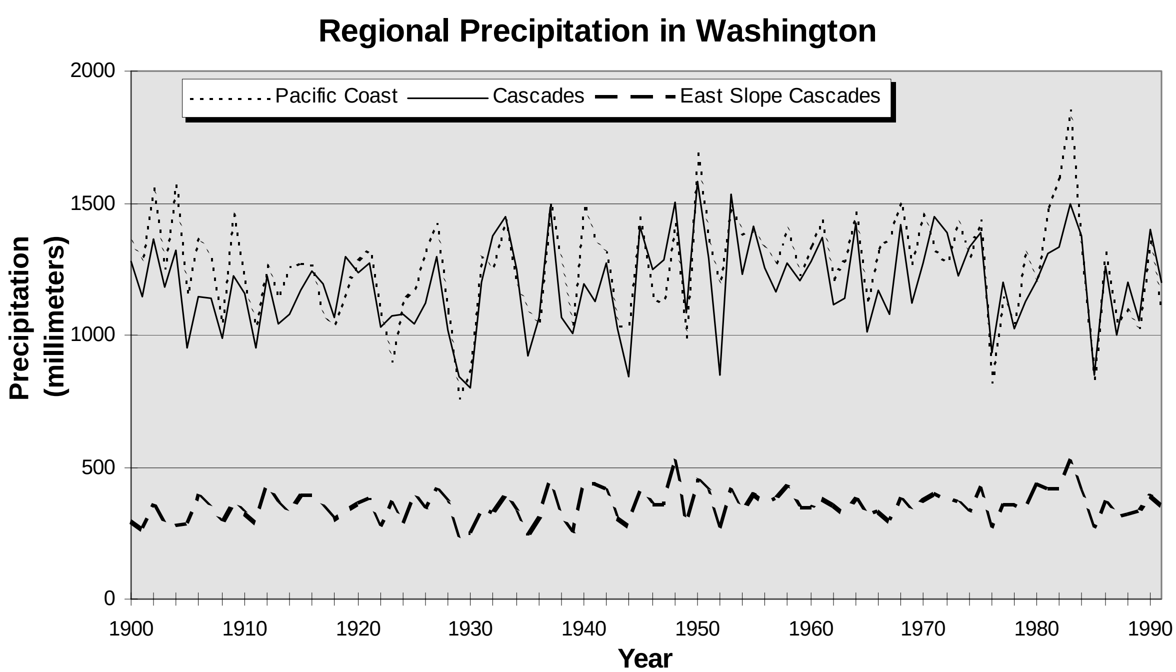



**FIGURE 2**

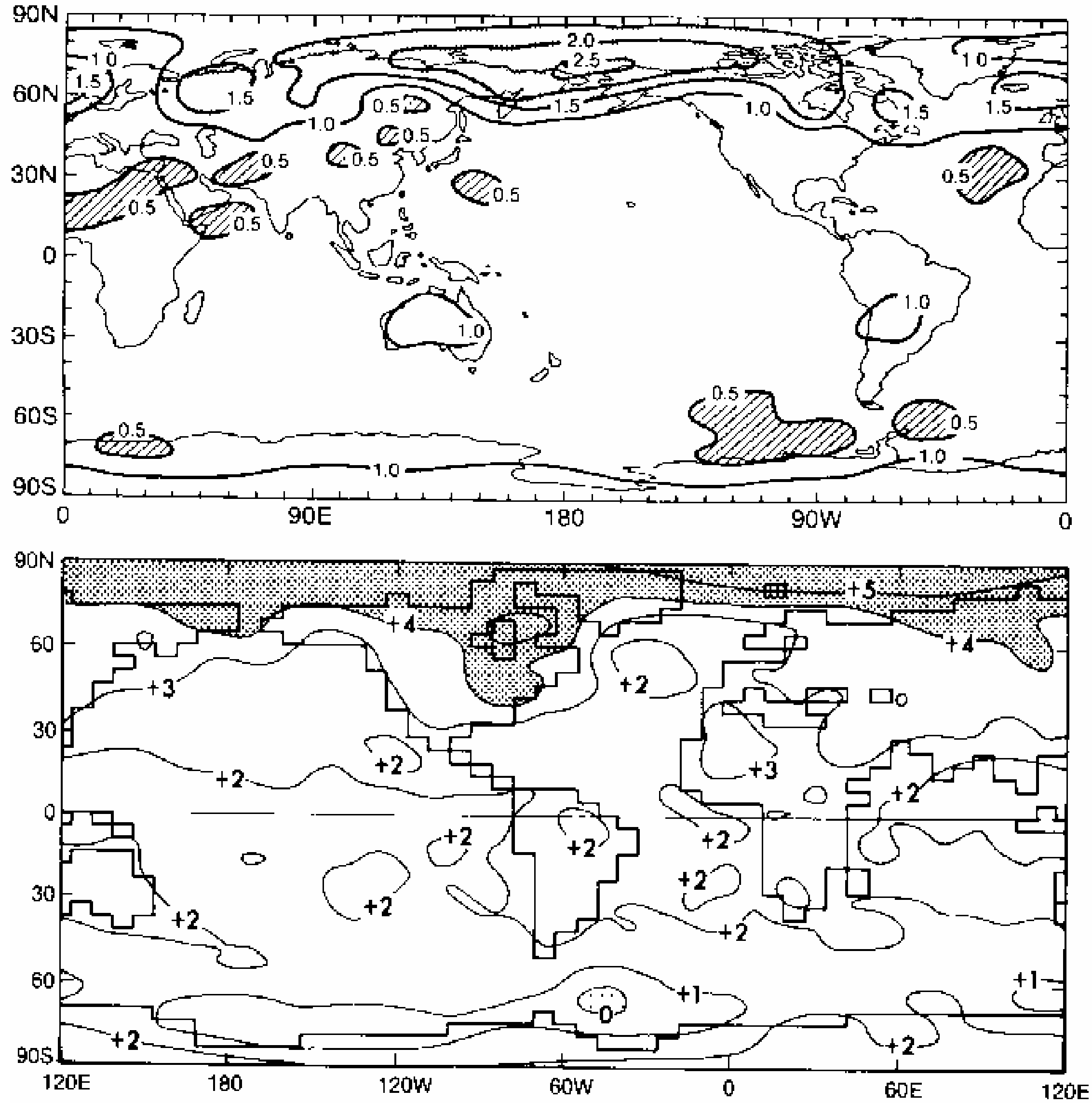



The assessment of climate change in Washington is based on data presented in the 1992 IPCC supplemental report. The IPCC report details climate response predictions of four coupled ocean-atmospheric GCMs to a transient doubling of carbon dioxide. One model indicates temperatures will rise less than 1°C for the Pacific Northwest-British Columbia region; two predict temperatures 1-2°C warmer; the fourth models a 2-3°C temperature increase. Perhaps even more important, the GCMs indicate little change in average rainfall and only a slight decrease in soil moisture.[10]

While acknowledging the uncertainty regarding any climate change prediction, this report assumes that the IPCC is the best judge of an estimate's credibility. Therefore, based on the data from the IPCC report, the report assumes a 2°C rise in temperatures in Washington as a result of a doubling of effective carbon dioxide levels in the atmosphere. In addition, average

[10] The progenitors of the four GCMs discussed in the IPCC supplemental report are (1) the National Center for Atmospheric Research (USA), (2) the Max-Plank Institute (Germany), (3) the Geophysical Fluid Dynamics Laboratory, (USA), and (4) the Meteorological Office, (UK). The climate change estimates for Washington used in this report were interpolated from graphical representations of GCM output. Two examples are below. The top figure below presents surface temperature changes estimates averaged over years 31 to 60 by the National Center for Atmospheric Research model. The bottom figure below presents temperature change estimates averaged over years 60 to 80 by the Geophysical Fluid Dynamics Laboratory model. Note that the temperature change predictions are greatest at high latitudes.

**Temperature Change (Celsius) Estimates Resulting from a Doubling of Atmospheric Carbon Dioxide Levels**



precipitation levels are assumed not to change. These predictions form the basis for assessing how climate change might affect Washington State.[11]

When discussing the potential effects of global climate change in Washington, it is important to remember that the uncertainties inherent in global climate change predictions are amplified in the regional assessments. The IPCC cautions that "there are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change." They go on to say that the "confidence in the regional changes simulated by GCMs remains low." Therefore, one must consider the following predictions of the effect of climate change in Washington as speculative. Nevertheless, speculation is important to provide the policy maker with some notion what climate change **may** have in store for the state.

## Human Health and Comfort

The first area of concern is human health and comfort. Using historical weather-mortality relationships, Nichols et. al. found that hot weather had a large mortality effect on northern and mid-west cities. In the south, where high temperatures are the norm, the effect was much smaller. In addition, they found that early summer high temperatures had a larger effect than late summer highs. The authors concluded that temperature "shocks" are an important factor in mortality and that humans acclimate to heat stress conditions. Table 2 presents Nichols' estimates of climate change induced heat related mortality for several cities.

**TABLE 2**

Estimates of Heat Related Mortality With Climate Change[†]

| City | Present Mortality | 2 ° C Temperature | |
|---|---|---|---|
| | | No Accl | Some Acclimation |
| Chicago | 173 | 177 | 88 |
| Cincinnati | 42 | 378 | 189 |
| Kansas City | 31 | 330 | 212 |
| Minneapolis | 46 | 209 | 105 |

---

11 Others predict more extreme climate change. Giorgi et. al., for example, nests a regional model within a GCM to predict a rise in northwest summer and winter temperatures of 4.7°C and 3.7°C. Giorgi also predicts a 25 percent increase in precipitation. While this technique may improve regional climate change predictions, Giorgi cautions that "*the primary purpose of this work was not to produce climate change scenarios (for example, for impact assessments) but rather to further test and evaluate the application of the nested … modeling methodology to climate studies. Our results are thus mostly illustrative in nature.*"

***The Evolving World***

When considering the consequences of climate change, one problem is to separate natural evolution from anthropogentic change. The very name "climate change" suggests our climate is static when, in fact, it is not. For example, from 600 to 1250 AD—the *Medieval Optimum*—Europe was warm. During this time Greenland was colonized and vineyards were cultivated in England. A *Little Ice Age* occurred between 1500 to 1850. Cold winters, reduced agriculture production and frozen canals characterized this period. Projecting consequences of global climate change in the face of such intrinsic change is extremely problematic.

Moreover, society is also changing and at speeds which exceed our ability to contemplate life 100 years in the future. Imagine the 1900 futurist predicting computers and other electronic devices, moon travel, nuclear energy or nuclear weapons, plastics, genetics, antibiotics and other medical advances. Moreover, people will adapt to climate change as they do with all changing circumstances.

The environment also evolves. Northwest paleontology studies reveal an evolving assortment of species and plants. Most plant communities are transient, seldom lasting for more than 2,000 to 5,000 years (Franklin). Agricultural crops also evolve. The National Academy of Sciences reports a ten years lifetime for any particular strain of major US agricultural crop.

Looking further back in time Benton reports tremendous changes in biological diversity. "*The diversity of all organisms increased rapidly during the Vendian and Early Cambrian to a global diversity of 280 families, then fell to 120 families in the Late Cambrian, and increased during the Ordovician to about 450. Diversity rose gradually from 450 to 600 families during the Paleozoic, fell to 420 families at the beginning of the Triassic, then rose rapidly to 1260 families at the end of the Cretaceous…*" Gould concludes that "*[m]ass extinctions have been recorded since the dawn of paleontology.*" and opines that such extinctions removed competitors to our biologic ancestors.

| | | | |
|---|---|---|---|
| San Francisco | 27 | 66 | 49 |

† From Nichols et. al., "Possible Human Health Impacts of a Global Warming,"

Nichols also observed threshold temperatures above which mortality significantly increases. Kalkstein and Davis corroborate this observation and reports Seattle temperature thresholds of 32°C for the summer and 3°C for the winter. Thus, if global climate change elevates summer temperatures above 32°C, one would expect increased mortality in Seattle. On the other hand, a reduction in winter time temperature excursions below 3°C, would decrease expected mortality.

While these findings underscore the health consequences of temperature extremes, there are three mitigating factors. First, in a process known as mortality displacement, Nichols' analysis suggests that 20 to 40 percent of the people who died during heat waves would have died soon afterward even if the heat wave had not occurred. Second, the temperature record over the past 100 years suggests that the observed 0.5°C temperature change resulted from rising nighttime rather than daytime temperatures.[12] A limited mortality effect should result if climate change continues to manifest itself in this way. Finally, both Nichols and Kalkstein indicate a high degree of acclimation to temperature. For example, summer and winter mortality temperature thresholds for Phoenix and Minneapolis are 45°C and -20°C, respectively. Acclimation of Seattle's population to a warmer temperature regime would reduced the mortality consequences of climate change.

Indirect health effects are less certain. It is probably correct to assume that disease vectors (e.g., ticks, mosquitoes) now confined to the tropics will spread into more temperate regions with global warming. Much less certain is how the diseases they carry will respond to the newly invaded areas. Bacteria, viruses and fungi are all affected by atmospheric conditions. Climate change may enhance or diminish the range and fortitude of these organisms. As one example, the Asian tiger mosquito, a vector of both dengue and yellowfever, was accidentally introduced into the southern U.S. The mosquito has now spread extensively to the east and north. However, this vector has yet to transmit either disease to man. Unfortunately, similar circumstances in Brazil brought about an outbreak of dengue (Rogers and Packer).

According to Dobson and Carper, the effects of tropical pathogens are likely to become worse as they move into a warmer and more humid temperate zone. Patz agrees *"The spread of infectious diseases will be the most important public health problem related to climate change"* (quoted by Stone). However, Hayes and Hussain could not statistically validate a temperature-disease relationship. They found neither a strong nor consistent relationship between temperature and the diseases tuberculosis, lyme disease, pertussis, malaria or typhoid fever. It is unknown whether a 2°C temperature rise would bring tropical diseases such as malaria, yellowfever and schistosomiasis to Washington. In any event, public health practices would likely help mitigate the prevalence and effect of these diseases should they reach this State.

Other effects of climate change on human populations include altered recreational opportunities. Recreation and tourism is especially vulnerable to climate change precisely due to its association with nature. Warming, for example would adversely affect snow skiing, while water skiing should benefit. That climate change will affect recreational opportunities in Washington is near certain. Whether the overall result is positive or negative depends on personal preferences.

[12] The rise in nighttime temperatures over the last 100 years illustrates that the manifestation of future temperature increases is far from clear. A 2°C temperature rise will likely vary between seasons and even between days. Some speculate more extreme summertime temperatures but warmer winters are equally probable.

## Agriculture and Vegetation

Climate change has the potential to affect agriculture in many ways: altered precipitation patterns, adjusted soil moisture, modified pest behavior and ranges, changed storm frequency and intensity. Farmers may need to modify crop selection, planting, irrigation and fertilization practices in response to climate change. Nevertheless, most reports suggest that U.S. farmers can adapt to all but the most pessimistic climate change scenarios. This finding is based on the carbon dioxide fertilization and improved water efficiency effect (see sidebar). Indeed, the general tenor of scientific reports regarding the effects of climate change on agriculture is one of guarded optimism. According to Rosenzweig *"…[agricultural] production in the developed world benefited from climate change."* Culotta is even stronger. *"For now, there's consensus that air rich in [carbon dioxide] will be a boon for many farmers, at least in developed nations."*

In Washington the agricultural effects do not appear severe. A 2°C temperature rise may expand the growing season (potentially allowing an additional crop rotation), reduce night frosts, and is within the tolerance limits of most cash crops. An EPA report (1989) suggests that climate change could increase agriculture acreage 5 to 17 percent in the Northwest. Though lower soil moisture may increase irrigation requirements. Schneider estimates that 3-4 percent more cropland will need irrigation. Presently, irrigation consumes only 6 percent of the Columbia basin flow and much of this water eventually finds it way back in the rivers as irrigation return flows (Department of Energy). McKenney suggests that the improved plant water use efficiency may largely counter the need for additional irrigation. Together, the combined effects of warming, carbon dioxide fertilization and improved water-use-efficiency, while uncertain, appear unlikely to adversely affect and may even benefit Washington's agriculture industry.

One very large complication in this assessment is potential changes in insect and fungi behavior. In a carbon dioxide rich environment plant nitrogen and water use efficiencies improve and less nitrogen is contained in shoots. Reduced nitrogen levels lower the nutritional value of a plant to insects.[13] Thompson found elevated carbon dioxide levels lowered both insect infestation and the severity of pathogenic fungal infection in a sedge crop relative to plants grown at ambient carbon dioxide concentrations. Conversely, fungal infection increased in a grass. For both types of plants the severity of insect infestation and the amount of tissue that each insect ate decreased. Climate change may also alter the range and resiliency of pests and thus introduce new pests and

***The $CO_2$ Fertilization Effect***

Laboratory studies consistently show that elevated $CO_2$ benefits plants. Plants assimilate carbon during photosynthesis in one of two processes. The C3 plants are less efficient than the C4 plants, wasting about half the carbon taken in. Thus, C3 plants benefit more from elevated carbon dioxide. After reviewing 70 studies of 37 plant species, Kimball reports that doubling $CO_2$ levels increased the yield of C3 plants (soybeans, rice, wheat, root crops, most tree species) by 35 percent and C4 plants (corn, sorghum, sugar cane) by 15 percent (see appendix A). However, others report that accelerated plant growth diminishes over time.

Carbon dioxide enrichment also appears to improve plant water use efficiency. The stomata (pores in plant leaves through which water escapes and $CO_2$ enters) narrow as $CO_2$ levels rise, reducing plant transpiration (water loss). Elevated $CO_2$ also appears to improve plant nitrogen use efficiency. Moreover, some studies suggest that high $CO_2$ levels stimulate biological nitrogen fixation which may alleviate nitorgen nutrient limitations over decadal time-scales. (Schimel)

The combined growth rate and water use efficiency responses appear to provide C4 crops a comparative advantage under drier conditions and C3 crops an advantage with constant water availability. However, the response of weather and nutrient stressed field crops is uncertain. Bazzaz and Fajer argue against increased growth under nutrient poor conditions.

[13] A secondary effect of an improved nitrogen use efficiency could be an increased level of photosynthates. These compounds are associated with plant defense mechanisms.

diseases to Washington crops. Overall, however, available information does not alter the basic premise that climate change is unlikely to adversely affect Washington's agriculture industry.

Climate change may have a greater import to plants outside of intensively managed agriculture. Seemingly small climate variances can significantly affect plant health and vibrancy. Harte experimentally heated plots in a Colorado meadow (carbon dioxide levels were not enhanced). He found that shrubs consistently grew better under warmed conditions whether wet or dry. Grasses showed no change in growth with warming and forbs consistently fared worse, especially under dry conditions. Thus, one might expect climate change alters the comparative advantages between plant species. However, the significance of such changes are not known.

***The World Food Supply***

While the threat of climate change to agriculture in Washington appears small, more severe consequences are projected in less developed parts of the world. In a report on climate change's effect on world food supply, Rosenzweig concluded that *" …production in developing nations [will] declined"*. This, of course, raises moral/ethical questions since the standard of living enjoyed by the developed countries may endanger those in the developing world.

## Forest Systems

Climate change will likely affect forests in similar ways to agriculture. For example, elevated carbon dioxide levels enhances tree growth; 23 to 40 percent for a doubling of ambient carbon dioxide levels (Kirshbaum et. al.). This accelerated growth even occurs in low nutrient soils. Kirshbaum reports large increases in root weight and hypothesizes increased nutrient use efficiency. For example, they predict a 12 percent increase in pine wood production at double current carbon dioxide levels even with nitrogen poor soil. Other experimenters report photosynthesis efficiency improvements and reduced leaf area in trees at elevated carbon dioxide levels. Norby hypothesizes that elevated carbon dioxide levels may improve trees ability to withstand environmental stress because less leaf area is needed to sustain growth. Over time, tests on individual trees found that the accelerated growth rates generally slowed. The cause of this slowing is not known; potential explanations include acclimation to elevated carbon dioxide levels, nutrient restriction, or limitations on roots imposed by the pots the trees grew in.

Extrapolating data from these short term-studies on individual trees to long-term effects for entire forest systems is problematic. Forests grow best under specific conditions: the right soil type, moisture, temperature. The changes brought about by climate change may upset those conditions sufficiently to force forest shifts. Since forests are long-lived, these shifts may not be noticeable for many, even hundreds of years. While mature trees will likely weather the climate changes, seedlings and saplings—the most vulnerable stage of tree growth—may not survive to replace the existing forest stock as it dies off. On the other hand, the carbon dioxide fertilization effect may partially mollify these effects by increasing the vitality of seedling and young trees.

***Forest Management Practices***

Until recently, a long standing policy of State and federal forestry agencies was to suppress all forest fires. During this period woody debris accumulated on the forest floor adding to the fuel available for fires. This has increased the likelihood of disastrous fires. These conditions increase the costs of forest fires: costs to put out fires, costs to replace/replant stands and costs in habitat loss. In areas with limited fire suppression activities, the effect of increased fires may be less significant.

In the Pacific Northwest, Douglas-fir is the dominant commercial forest species. The upper elevation limit of coastal Douglas-fir is determined by the winter snowpack, which physically damages seedlings. Should the rise in temperature elevate the snow line, the upper elevation limit of Douglas-fir on the west side of the Cascade Mountains may move up-slope. Based on this logic Leverenz projects that Douglas-fir [and western hemlock] will *"…expand or maintain its present position over most of its commercially important range. However, the species [does] decrease in… eastern Washington."* Franklin et. al. dispute this finding noting Douglas-fir's aversion to wind exposed environments even when moisture and temperature conditions are within its tolerances. They argue that rather than moving in "intact multi-species communities," forest shifts will depend on micro area conditions. Overall, Franklin predicts relatively small reduction (5 percent) in forested area in western Washington but a large loss (26 percent) east of the Cascades. Conversely, Melillo projects a 9 percent increase in "net primary production" for temperate coniferous and mixed forests (similar to Washington's forests) from the combination of carbon dioxide levels at 600 parts per million and the associated climate change.[14]

Another concern about the effect of global climate change on forests includes the potential for an increase in severity and number of forest fires. Forest fires result when four forces converge: fire ignition, adequate fuel (wood and biomass debris), low fuel moisture levels, and dry weather. Once ignited, forest fire behavior is guided by fuel, weather and topography.

There are two fire seasons in Washington. The spring season occurs when trees are relatively dry before emerging from their winter dormancy. Given the high precipitation during the spring, a warming may bring on this fire season somewhat earlier but is unlikely to increase the severity or number of fires during this period. The fall fire season results from trees drying out over the summer. During this season, climate change could significantly effect forest fires. Warmer temperatures would increase the rate of drying and lengthen the fire season. Together these factors are likely to result in both an increase in the number of and area burnt by forest fires. Indeed, Price studied the effect of doubling carbon dioxide concentrations on lighting-caused fires. He estimated a 44 percent increase in the number of these fires in the northwest. He also estimated an increase of 78 percent in the forest area burnt by fires for the entire United States.[15]

In sum, there is no reason to believe that climate change will denude the Pacific Northwest of forests. However, climate change will create opportunities for change in the forestscape. Over the long run, altered comparative advantages between tree species may change the climax species of an area. Furthermore, forests may expand into currently inhospitable environs while other areas will no longer be able to sustain forests. Natural forests with their greater diversity are likely to show more resilience to climate change than intensively managed mono-stand forests.

## Fish and the Fishery Resource

In general, climate change will likely affect fish in three ways. Any changes to rain fall patterns, whether increasing, decreasing, or occurring at a different time of the year, are important to fish. Second, as water density changes with temperature, changes to stratification and circulation patterns may result. Finally, water holds less oxygen at elevated temperatures. Therefore, climate change may physiologically constrain a water body's organism carrying capacity.

---

[14] Net Primary Production is the amount of carbon captured by land plants through photosynthesis each year. It provides one measure to estimate the response of regional ecosystems to the combined effects of carbon dioxide fertilization and global warming.

[15] Around 80 percent of fires in Washington are directly caused by human carelessness or intention. Global climate change may create conditions that increase the number of these actions that turn into forest fires and the intensity of those fires. However, since these fires are preventable, a philosophical question over whether climate change (which enhances the conditions of fire) is at fault for increasing forest fires or man (the initiator of fire).

Francis investigated climate change effects on the aquatic food chain. He argues that changes in physical ocean processes (e.g., currents that transport eggs and larval fish from spawning to nursery grounds; water column mixing that affects food production and availability) will affect fish more directly than climate change.. Uncertainty regarding how the marine food chain functions leads Francis to conclude that *"…we cannot confidently predict how [the ocean food chain and ultimately fish themselves] will be affected by climate change."* Table 3 presents some potential effects of climate change on ocean fisheries.

**TABLE 3**

**Potential Effects of Climate Change on Ocean Biota and Fisheries†**

| Climate Related Effects | Biotic Effects | Projected Effects on Fisheries |
|---|---|---|
| 1. Increased mean water temperature. | Increased growth and development rates and metabolic demands of all species. | Increased survival and yield, subject to changes in predator/prey abundance. |
| | Poleward and seasonal shifts in productivity and predator/prey distribution. | Poleward shifts of ranges and migration patterns, subject to suitable habitat. |
| 2. Increased surface vertical stability | Turbulent waters: increased photosynthesis due to decreased diffusive nutrient supply. | Increased potential yield due to increased food supply. |
| | Stratification of waters: decreased photosynthesis due to decreased diffusive nutrient supply. | Decreased potential yield due to decreased food supply. |
| | Earlier spring production increased plankton patchiness. | Changes in feeding ability of fish and predators; uncertain net effect on yield. |
| 3. Decreased latitude and seasonal sea-ice extent. | Decreased surface stability; lower intensity by greater duration or primary production. | Increased survival due to increased food supply; modified by effects on feeding ability and distribution of predators. |
| 4. Weakening, poleward and seasonal shifts in storm tracks and surface turbulence | Areas of decreased storminess and turbulence. | Same as (2) above. |
| | Areas of increased storminess and turbulence. | Opposite of (2) above. |
| 5. Weakening, poleward and seasonal shifts in wind-driven surface currents and coastal upwelling | Poleward and seasonal shifts in primary production patterns depending on orientation of coastline. | Increased yield if food supply increases; lower yield if food decreases. Increased survival of eggs and larvae if drift loss from nursery areas decreases; decreased survival if drift loss increases. |
| 6. Temperature increase and high latitude increase in net precipitation and runoff | Poleward species shifts due to poleward shifts in salinity patterns. | Local survival affected by drift loss changes due to runoff, as in (5) above. |
| | Increased net precipitation as in (2) above. | Same as (2) above. |
| | Decreased net precipitation opposite of (2) above. | Opposite of (2) above. |

† From Francis and Sibley.

Ray et. al., concludes that widespread extinction of aquatic organisms is not likely as a result of global climate change. But that widespread changes in community distributions and composition are probable. These changes will closely track global warming in time, because of the mobility, large ranges, high fecundity, and rapid growth rates of most marine organisms.

In Washington state, climate change will likely benefit some anadromous and resident fish and harm others. Neitzel et. al., projected the effects of climate change on 60 Pacific Northwest salmon and steelhead fish subspecies: 14 were adversely affected; 24 were unaffected; and 21 benefited. Others are concerned that climate change would ultimately introduce even more stress on fish stocks already depleted due to other environmental factors. Should climate change increase the importance of irrigation and electricity production relative to the position of fish, their existence will become even more tenuous.

## Biodiversity

Since time immemorial, climate fluctuations have continually stressed and altered natural ecosystems. The biodiversity concern with regard to global warming is whether this stress has prepared species to cope with the coming warming.

EPA (1989) suggests that temperature isoplaths will migrate hundreds of kilometers towards the poles under climate change. The question is whether the dispersal capabilities of species are sufficient to stay within their optima climatic zone, and whether species could rapidly colonize new areas. Species, such as plants propagated by spores or "dust" seeds, may be able to match the needed migration rates on their own. Others will require human assistance, particularly given the presence of dispersal barriers. Some mobile animals may shift rapidly, the distribution of others may be limited by the availability of co-occurring plants and suitable habitat. Behavior may even restrict those animals physically capable of moving great distances. Dispersal rates below 2.0 kilometer per year have been measured for several deer species, for example (Peters). Finally, review of biodiversity changes associated with the past climatic changes reveal that species exhibit individualistic patterns of changes. Therefore, climate change will affect ecosystem composition.

According to Tracy, temperatures can affect habitat quality. It governs the time of day and time of year when populations within a community are active. Increased temperatures can affect the distribution and abundance of animal species. It may reduce the number of species in an ecological community (Tracy). Thus, temperature changes caused by climate change may catalyze major changes in animal populations and communities. Potential changes to agriculture, forestry and fishery from climate change were discussed above. Other potentially important effects include:

**Insect Effects:** For many insects, development rates, speed and distance of movement, and fecundity will generally increase with temperatures and humidity. These changes should have pronounced effects on many ecological processes.

**Soil Effects:** According to Whitford, most components of the soil biotic community have wide ranges of tolerance to temperature and moisture fluctuations in their environment. Further, the short life cycle of these organisms should permit genetic adaptation to shifts in the soil micro-climate. Therefore, it is unlikely that the projected climatic changes will result in extinction of soil organism species. Climate change may, however, cause shifts in relative abundance of species. Since processes such as decomposition and mineralization are the result of the activities of these species, the rates and patterns of such processes will depend on the species active. Because of the many feedback loops among soil organisms, plants, and the physical-chemical environment of the soil, we can expect the temperature induced soil biota to affect the ecosystem.

***Conservation Efforts Under Climate Change***

After considering the effect of climate change on conservation efforts, Graham concludes that new management strategies may be necessary:

*Most conservationists consider the extinction of species unacceptable, and substantial resources have been expended in their conservation. Similar efforts have been made for the conservation of communities. However, the ephemeral nature of communities, on a geologic time scale, particularly due to climatic change, suggests that significant resources should not be devoted to trying to conserve specific community types… Rather, emphasis should be on management strategies that allow maximum survival of species and genetic strains and that allow natural communities to evolve.*

*For species to survive in the long run, they must respond to environmental change, in part by tracking shifting climatic environments. In the case of mammals within reserves, this means that the reserve should ideally be large enough and located so that species could change their geographic distributions. During this process new community patterns would evolve.*

Extending biotic projections to Washington State is no minor challenge. Particularly because for most species, the links between climate and ecosystems are poorly understood. And where the links are known, the evidence suggests that species are often more affected by extreme events rather than changes in mean conditions (Myers and Lester). Moreover, we do not as yet understand important linkages between the atmosphere, soils, water, biota and global warming which could exacerbate or mitigate biologic effects.

## Energy Demand and Production

Climate change will affect northwest electric demand in conflicting ways. Warmer temperatures will lessen the winter heating demand. In 1981, the Bonneville Power Administration (BPA) estimated that a 1°Fahrenheit rise in temperature would decrease peak and average electricity demand in the northwest region about 270 and 262 megawatts, respectively. Thus, a 2°C rise would lower peak electricity demand almost 1000 megawatts and average electricity demand 950 megawatts.[16] Conversely, warmer temperatures increase summertime cooling demand. Overall, the annual change in electricity consumption is uncertain but anticipated to be small. However, a lower winter demand could benefit Washington since supply system stress is greatest at this time.

With regard to electricity production, Washington is especially sensitive to climate change due to dependence on the hydropower system to meet base electric needs. Indeed, according to Fleagle, *"Changes in water resources may be the most important of the consequences of greenhouse warming."* To the extent that changes to temperature, precipitation patterns and snow pack volumes alter seasonal runoff, hydropower production will change.

Warmer temperatures will raise the mountain snowline and decrease snowpack area. A lower snow pack volume will increase wintertime river flow and decrease summertime flow. Fleagle argues that the increased summer-winter flow variation might immeasurably complicate river management efforts.[17] On the other hand, an unpublished Battelle Laboratory report found that runoff under warming may better follow electricity demand patterns. Battelle examined monthly generation capacity under climate change and found that *"hydropower would be generally more in excess of the needs of the residential and commercial sectors at more times of the year than under current flows and current demand. Only June appears to be an exception."*

Lower spring and summer flows are also likely to degrade the water supply in late summer. However, there are contravening studies. Skiles concludes that surface runoff in the arid and semi-arid western U.S. will change little due to climate change. Taken together, it is unclear whether the weather induced changes in demand and supply produce a

***Hydroelectricity Production***

Washington's hydropower system is driven by rain runoff, snow melt and controlled reservoir releases. Snow melt from early spring to mid-summer fills dam reservoirs and generates electricity. Continued snow melt and reservoir water produce electricity during the summer and fall season. Winter electricity demand is principally served through reservoir water.

At its mouth, the Columbia River has an average annual runoff of about 198 million acre-feet (275,000 cubic feet per second). Total Columbia river system storage space equals 55.3 million acre-feet (including Canadian dams). Hydroelectric dams on the Columbia and Snake Rivers annually produce 18,500 megawatts of electricity. BPA estimates that a million cubic feet of water represents about 1.1 billion kilowatt hours of electricity.

[16] A 2°C is approximately equal to 4°F. Population and economic growth significantly increased electricity demand since 1981. Therefore, a 2°C temperature rise would probably lower wintertime peak and average demand for electricity even more than the estimates presented above.

[17] The Columbia river system is managed for conflicting purposes of power generation, irrigation, transportation, salmon protection and recreation.

more favorable or less favorable energy situation in Washington. The current climate models do not yet paint a clear picture of the energy consequences of global climate change.

## Sea-Level Rise

Since water expands as it warms, a potential consequence of climate change is sea-level rise. Over the past 100 years the sea level has risen globally about 0.12 meters. Recent estimates suggest that climate change may accelerate sea level rise to about 0.4 meters through 2100 (Wigley and Raper).[18] The effect of such a sea level rise on Washington is not straight forward due to motions of the earth's crust. Much of Washington's Pacific coast is currently rising relative to the ocean: the land continues to rebound from the great weight upon it during the previous glacial period and the geological subduction of the Juan de Fuca plate under the North American plate is tilting the coast upwards (Savage and Liscowski). Northern coast uplift should roughly equal the projected sea-level rise. Along the southern coast, the sea level should rise about 0.2 meters through 2100. Sea level rise will have a greater effect over the mid-coastal area. Aberdeen, for example, may experience the full 0.4 meter rise. For northern Puget Sound a rise of about 0.3 meters is likely. Over the middle and southern Puget Sound the combination of geologic subsidence and sea-level rise may raise the sea-level more than 0.5 meters.

The Department of Ecology (Ecology) projected the consequences of 0.5 meter sea-level rise on state wetlands (Park et. al.). The study found a large loss of tidal flats. This could significantly decrease shellfish, including oysters and clams; it may also reduce habitat for diving ducks and brants. In contrast, salt water marshes expanded, gradually reclaiming diked lowlands. The spread of salt marshes should benefit Chinook salmon, some water fowl and other wildlife. Freshwater marshes and swamps could slightly increase in area. Some existing wetland, marine and estuarine communities may migrate inland but other adverse effects are not anticipated. Of course, the actual effects of the sea-level rise depend on diking and bulkheading activities.

## Storms

One frequently mentioned potential effect of climate change is an increase in storm frequency and severity (Erye). The concern is that storm causing atmospheric temperature gradients will increase under climate change.[19] One study used the proportion of annual precipitation falling on the rainiest day of the year as a proxy for storminess (Stevens). After tracking changes in heavy down-pours from 1910 to 1994, this study concluded that storminess has indeed increased over the eastern and central U.S. However, no change in storminess was found in the western U.S., including Washington state.

Other studies of storminess assess areas outside of Washington state. Dessens, in a study of France (a similar latitude to Washington) found a correlation between nighttime temperatures

[18] A much less likely but infinitely more catastrophic result of global climate change would be the break up of the east Antarctic ice sheet. The east antarctic ice sheet is larger than the continental United States and extends over 4 kilometers in altitude in some places. It locks up a mass of water which, if melted, would raise world sea levels by around 60 meters (Sugden). However, such a breakup is extremely unlikely even under pessimistic climate change predictions (Sugden). Moreover, the size of ice sheets in dry cold polar environments is restricted more by precipitation rather than by temperature. Should additional snowfall accompany climate change, as some GCMs predict, the ice sheet may actually expand rather than decrease in size.

[19] Seemingly small changes in wind patterns apparently can, for example, trigger an El Niño event. And El Niño events significantly affect weather patterns throughout the Pacific basin. However, no one is sure what causes the wind patterns to change and bring on an El Niño event.

and hailstorm severity.  Hail damage increased 40 percent for every 1°C rise in nighttime temperature.  On the other hand, Kukla and Karl, conclude that that the temperature change recorded so far (warmer night time and no change in day time temperatures) will moderate rather than amplify weather extremes.  Studies of tropical weather patterns present conflicting results. Lighthill's study of tropical cyclones predicts a response to climate change so small that it would be swamped by the large natural variability in storm numbers and intensity.  Nadis found a 100-fold increase in lighting strikes with a 2°C jump in temperature.  These discussions of altered storms patterns outside of Washington are presented for illustrative purposes only; their relevance to storms in Washington (if any) is not known.

## Economic Effects

Global warming is not anticipated to significantly change Washington's economy.  Using the methodology of Nordhaus, sectors of the State's economy are ranked according to their vulnerability to climate change (see Table 4).  The economic sectors most at risk to climate change—agriculture, food products, forestry, wood and paper products, and fisheries—account for less than 8 percent of state economic activity.  And the agriculture and forestry sectors may actually do better under climate change.  Sectors at a moderate risk to climate change total slightly more than 8 percent of the economy.  Fully 85 percent of the State economy is in areas that appear insulated from the adverse climate change consequences.  Furthermore, should the service sector of the economy continue its expansion, the portion of Washington's economy at risk to climate change will continue to fall.

However, the above assessment ignores the fact that Washington annually exports nearly $40 billion worth of goods and services (1995 Washington State Yearbook).  Any assessment of the effect of climate change on the state's economy should consider changes in the ability of foreign persons to continue to purchase our goods.  Unfortunately, such an assessment is outside the scope of this report.  This report reviews how climate change might affect Washington's ability to produce goods, not whether there will continue to be buyers for those goods.

TABLE 4

**Economic Activity in Washington State by Vulnerability to Climate Change, 1990**

| Sector | Washington State Gross Business Income | |
|---|---|---|
| | Value (millions)† | Percent of Total |
| *Potentially Highly Affected* | | |
| Agriculture | 3,084 | 1.21 |
| Forestry | 195 | 0.08 |
| Fisheries | 213 | 0.08 |
| Food Products | 6,157 | 2.41 |
| Lumber and Paper Products | 10,115 | 3.96 |
| **Subtotal** | **19,764** | **7.74** |
| *Potentially Moderately Affected* | | |
| General Building Construction | 5,504 | 2.15 |
| Heavy Construction | 2,105 | 0.82 |
| Special Trade Contractors | 5,662 | 2.22 |
| Live Stock/Dairy | 1,280 | 0.50 |
| Water Transportation | 1,208 | 0.47 |
| Energy and Utilities (electricity, natural gas) | 5,540 | 2.17 |
| **Subtotal** | **21,299** | **8.33** |
| *Generally Unaffected* | | |
| Mining | 238 | 0.09 |
| Aircraft and Ship Building | 25,272 | 9.89 |
| Other Manufacturing | 16,329 | 6.54 |
| Railroads and Motor Freight | 4,990 | 1.95 |
| Communications | 3,865 | 1.51 |
| Wholesale Trade | 73,903 | 28.91 |
| Retail Trade | 48,772 | 19.08 |
| Finance, Insurance and Real Estate | 14,544 | 5.69 |
| Services and Other Businesses | 26,249 | 10.27 |
| **Subtotal** | **214,162** | **83.93** |
| **Total All Industries** | **255,614** | **100.00** |

† Economic values from the 1993 Washington State Yearbook except: agriculture and livestock values from the Washington State Department of Agriculture.

## Summary

While not every potentially important result of climate change is discussed above, it appears unlikely that Washington will experience severe adverse effects through the years 2050-2080. A 2°C warming is not anticipated to threaten human health, agriculture may do better due to the carbon dioxide fertilization effect, eastern Washington may loose some forest land, hydropower production appears minimally affected, the fish effects are uncertain; and the economic risks appear limited. Of more concern is the consequences of sea-level rise, especially for the central-south Puget Sound and central coastal areas.[20]

[20] Again, this study does not look beyond the effects expected from a doubling of atmospheric carbon dioxide levels. Since there is no reason to assume greenhouse gas concentrations will stabilize at this level, the projected changes must be considered as points along the global climate change path.

It is important to remember that these projected climate change consequences are speculative. Understanding of the global climate system is incomplete, as are societal and environmental responses to a changing climate. Moreover, surprises—consequences (both good and bad) outside our ability to predict with current knowledge and understanding—are possible as climate, environments, and species interact and adapt in unexpected ways. The discussion above is based on current understanding of the global climate system; an understanding that is sure to evolve as more is learned about climate change.

Finally, the research done for this report suggests that climate change is probably not an issue of human survival: humans can adapt to the anticipated changes. Rather, the decisions before us concern the steps we are willing to take to protect the environment we know against the risks of climate change.

***Adaptation to Climate Change***

The National Academy of Sciences summarized the likely response of affluent societies to climate change as follows:

*[Affluent societies] have reduced their sensitivity to natural phenomena in many ways. Overall, the trend is toward transportation, communications, and energy production systems less sensitive to climate. Improved technology and social organization also seem to have lessened the impacts of climate fluctuations on food supply over the last 100 years. In the time frame over which the effects of greenhouse warming are felt, more societies may become more robust with respect to climate change.*

# GREENHOUSE GASES AND WASHINGTON STATE

## EMISSIONS OF GLOBAL WARMING GASES IN WASHINGTON STATE

Washington's emissions differ markedly from national averages. Most of the state's electricity comes from hydro or nuclear sources, both zero greenhouse gas emitters. Washington's forests remove about one-third of the carbon dioxide equivalent emissions (nationally they remove only 12 percent). A third difference is the aluminum industry's emissions of carbon tetrafluoride which accounts for 10 percent of Washington's greenhouse gas emissions. We consume more fuel for transportation than other areas. For example, we consume large quantities of jet fuel, much of which is used for Pacific rim flights. On a per capita basis, Washington emits about 20.3 tons of carbon dioxide equivalent gases per year, about 97 percent of the national average.

There are four principle greenhouse gases emitted in Washington: carbon dioxide, methane, nitrous oxide and carbon tetrafluoride. To ease comparisons, Table 5 reports emissions of all greenhouse gasses in terms of their carbon dioxide equivalent.[21] Net carbon dioxide equivalent emissions are estimated to grow from 91 to 110 million tons between 1990 and 2010, a 20 percent increase. The most important emission sectors are residential, commercial, industrial, transportation and forest products.

Table 5 estimates of Washington's greenhouse gas emissions are based on information contained in two Washington State Energy Office reports (Kerstetter)—with some adjustments. Emissions estimates from the forest products industry were revised in two ways. First, 1990 forest growth rates were re-estimated using data from Adams—already the basis for the 2010 estimates. Using the same data source improves confidence in estimates of relative changes in forest growth and

[21] The influence of a gas on climate depends on its radiation absorption capacity and its length of stay in the atmosphere. Global warming potential (GWP) index numbers were developed to compare the effect of the different gases. The GWP number indicates the global warming impact of a gas relative to $CO_2$. The GWP numbers of Washington's four dominant gases are:

| | | | |
|---|---|---|---|
| Carbon Dioxide | 1 | Nitrous Oxide | 270 |
| Methane | 11 | Carbon Tetrafluoride | 8000 |

carbon dioxide sequestration. The Adams data lowers 1990 forest carbon dioxide sequestration by about 20 million tons.[22] In addition, 20 percent of long-term wood products and 10 percent of manufactured wood items were assumed to permanently sequester carbon. Housing data indicate that about 25 percent of homes stand for more than 100 years. Similarly, furniture can

**TABLE 5**

**Carbon Dioxide Emissions Equivalent by Source (in thousands of tons)**

| Source | 1990 | 2010 |
|---|---|---|
| **Energy Related** | | |
| Residential | 9,970 | 12,939 |
| Commercial | 5,870 | 9,100 |
| Industrial | 22,560 | 32,270 |
| Transportation | 46,637 | 66,080 |
| Coal Mining | 114 | 121 |
| *Subtotal* | 85,151 | 120,510 |
| **Materials Production Related** | | |
| Cement Production | 244 | 618 |
| Lime Production | 456 | 456 |
| Aluminum Production | 6,507 | 3,560 |
| Land fills | 4,827 | 3,066 |
| Forest Long-Term Products | 14,160 | 15,180 |
| Forest Short-Term Products | 4,400 | 3,900 |
| Forest Residue | 14,200 | 15,400 |
| Forestry Slash Burns | 1,063 | 427 |
| Net Annual Forest Growth | (42,600) | (51,500) |
| *Subtotal* | 3,013 | (9,511) |
| **Agricultural Related** | | |
| Range Cattle | 608 | 608 |
| Dairy Cattle | 228 | 228 |
| Beef Cattle | 133 | 133 |
| Other | 160 | 160 |
| Dairy Manure | 506 | 506 |
| Broilers & Layers | 44 | 44 |
| Beef Cattle Manure | 18 | 18 |
| Swine Manure | 13 | 13 |
| Other Manure | 3 | 3 |
| Fertilizers | 790 | 790 |
| Field Burning | 90 | 108 |
| *Subtotal* | 2,593 | 2,503 |
| **Land-Use Related** | | |
| Convert Forests to Other Uses | 4,319 | 4,319 |
| Sequestration in Forest Reserves | (3,800) | (8,440) |
| Wetlands | 149 | 146 |
| *Subtotal* | 668 | (3,975) |
| **Total Emissions** | **91,425** | **109,527** |

last for more than 100 years. These changes lowered the estimated carbon dioxide emissions about 3 million tons per year for both 1990 and 2010.

[22] Generally speaking, the forest products sector is the most uncertain among Washington's carbon dioxide sources and sinks. The estimates presented in this report are likely to continue to evolve as research sheds light on the many partially understood biological and ecological processes.

A second adjustment made to the emission inventory was to account for the federal effort to reduce carbon tetrafluoride emissions from the aluminum industry. This effort is part of President Clinton's U.S. Climate Change Action Plan. The federal government is developing emission reduction targets in partnership with the aluminum industry. To meet these targets the industry must improve process controls to prevent situations that produce carbon tetrafluoride from developing. While participation in this program is voluntary, aluminum companies are likely to join given economic benefits. The federal government expects this effort to reduce emissions an average of 45 percent. This lowers the carbon dioxide equivalent emission estimate for Washington by 2 million tons in 2010.

***Aluminum Industry Emissions***

Aluminum refining requires removing the oxygen from alumina ($Al_2O_3$). To accomplish this, an electrical current is passed through an alumina/fluorine salt bath (between carbon electrodes). This separates and removes the oxygen. However, if the alumina level falls too low, the salt bath begins to decompose. In such an event, fluorine from the salt reacts with the carbon electrode to create carbon tetrafluoride compounds.

The final revision was to take into consideration federal efforts to improve the efficiency of residential appliances. Appliance efficiency mandates are part of the Energy Policy and Conservation Act and its amendments. The Act legislatively sets efficiency standards for thirteen categories of household appliances and establishes a schedule for the Department of Energy (DOE) to revise those standards. DOE has tightened the efficiency standards for clothes washers, dishwashers, and clothes dryers, furnaces, refrigerators, and freezers. DOE also proposed more stringent standards for room air conditioners, water heaters, direct heating equipment, mobile home furnaces, kitchen ranges and ovens, pool heaters and television sets (59 FR 10464). Finally, DOE issued an advanced notice of proposed rulemaking regarding dishwashers, clothes washers and clothes dryers efficiency (59 FR 56423). Ciliano projects that together these efficiency improvements will reduce the residential electricity demand by 18 percent and natural gas consumption by 13 percent. Based on these estimates, 2010 greenhouse gas emissions from the residential sector were revised downward by 1.8 million tons.

## REDUCTION STRATEGIES

Table 5 clearly illustrates that no single activity in Washington dominates greenhouse gases emissions. Therefore, no single measure can stabilize this state's contribution to global climate change. Significant reductions in greenhouse gas emissions will require a broad range of mitigation programs. This report reviews 49 potential greenhouse gas mitigation programs. Criteria important to the evaluation of greenhouse gas mitigation programs are:

- *Flexibility*. The timing and effects of climate change are uncertain. Therefore, a greenhouse gas mitigation program needs to succeed under a variety of conditions. For example, chlorofluorocarbons were once thought to significantly contribute to the earth's global warming potential; a conclusion now discredited. As a result, a mitigation strategy that relied solely on the international agreement to ban chlorofluorocarbon production would be a failure. A flexible mitigation strategy will allow mid-course refinements to adapt to our evolving understanding about climate. Therefore, it is important to understand the flexibility of each potential mitigation strategy.

- *Economic efficiency*. Washington state faces a wide range of social needs and desires as we approach the twenty-first century. These needs include, for example, health care, education, public safety, infrastructure upgrades, the arts and the environment. Given these competing interests and the limited moneys available, it makes sense to adopt the cost effective mitigation programs; programs that eliminate the most greenhouse gas for the least cost. One sub-category of strategies are those with no net cost. Their energy savings more than offset their costs. These are often referred to as "no regrets" options.

- *Other Benefits*. This criteria is closely related to Economic Efficiency. Mitigation strategies can often meet societal goals beyond limiting greenhouse gas emissions. Actions that improve social welfare, enhance environmental quality, increase employment, or enhance food security fall under this category. For example, efforts to reduce motor vehicle use also help reduce congestion and lower the trade deficit by limiting the need for foreign crude oil. Similarly, improvements in energy efficiency may increase employment (Laitner). A virtue of such greenhouse gas mitigation policies is that they generate benefits even if the risk of climate change turns our to be less serious than presently thought.
- *Feasibility*. Greenhouse gas mitigation strategies must be consistent with legal, political, and societal realities. The optimal strategy is irrelevant if it exceeds the bounds of political acceptability. For example, while we report the potential for significant carbon dioxide reductions from increasing the gasoline tax by $1.00 per gallon, the likelihood that such a tax would be enacted is very small.

This report targets the residential, commercial, industrial, transportationsectors, and electricity production assuming that these activities with the highest emissions will yield the largest reductions. However, we avoid programs clearly outside the authority of Washington policy makers to implement, such as automobile fuel efficiency standards. Further, only presently available technologies are considered. While some developing technologies promise substantially lower emissions (e.g., hydrogen powered vehicles) solutions to their remaining technical difficulties or high cost may prove elusive.

In terms of greenhouse gas emissions, there is often overlap between and among these sectors. For example, little is gained (in terms of greenhouse gas emissions) from reduced residential electricity use if the electricity supply is from a renewable resource. Also, telecommuting reduces the benefits of car pooling somewhat. Therefore, please note that emission reduction estimates presented herein are <u>not</u> additive.

The number of greenhouse gas mitigation strategies reviewed for this report prevented a highly detailed review of each potential program. Therefore, the estimated emission reductions and costs only identify the most promising programs. Any effort to implement these programs should begin with a more detailed analysis of their cost and potential emission reductions. Part of this detailed analysis must include estimates about the marginal generating resource, the price of fossil fuels and the efficiencies of fuel using items. Some of the more general assumptions used for this report are:

| Marginal Resource | Generating Efficiency | Carbon Dioxide Emissions | Fuel Price | | Interest Rate | Line Loss |
|---|---|---|---|---|---|---|
| | | | Natural Gas | Electricity | | |
| Combined Cycle Combustion Turbine | 50% | 365.7 g/kWh<br>0.81 lbs/kWh | $2.5/MBtu | 30 mills/kWh | 5% | 10% |

Finally, choosing a policy instrument to implement a greenhouse gas mitigation program is also extremely important. Generally, policy instruments fall into three areas:

1. **Economic Incentives**—direct taxes granting or eliminating tax breaks, subsidies, granting of regulatory exemptions, making pricing more efficient;
2. **Public Investment**—research and development, education, new infrastructure, maintenance of existing infrastructure, also withholding investment in greenhouse gas generating activities; and
3. **Regulation**—efficiency standards, zoning, building codes, fuel use requirements, speed limits, and travel restrictions.

## The Residential Sector

The residential sector is a large source of carbon dioxide emissions; almost 10 million tons per year in 1990 rising to nearly 13 million tons in 2010. Sheer increases in the number of people and households underlie much of this growth. Technological improvements and building efficiency codes—such as the Washington State building energy code—help limit growth in this area. Indeed Byers estimates that by the year 2005, Washington's current energy code will annually reduce carbon dioxide emission by some 3.3 million tons over what they otherwise would have been. Nevertheless, as discussed below, considerable potential remains to further improve energy efficiency in the residential sector and thereby reduce greenhouse gas emissions.

**Space Heat In New Construction.** Washington has a long and active history with residential energy codes. First adopted in 1977, the energy codes were upgraded in 1980, 1986, and again in 1991.[23] The present code divides the state into two climate zones: zone 1 encompasses the western and southern portions of the state while zone 2 covers the northeast.[24]

WSEO recently contracted with Ecotope, Inc. to analyze the cost and energy savings of code upgrades. Modifying this analysis for carbon dioxide emission reductions reveals that the current residential energy code already employs most cost-effective conservation measures. (See Tables B-3 and B-4 in Appendix B) However, upgrading to class 35 windows (e.g., windows with an insulation value of U-3.5) is cost-effective—the energy expenditure savings exceed the cost of the upgraded windows. The per house annual carbon dioxide emissions reductions from upgrade measures is presented in Table 6. However, the model home that serves as the basis for

---

[23] In a recent assessment of state energy codes the Alliance to Save Energy, an energy-efficiency advocacy group, gave Washington's code a "B+."

[24] Residential Energy Code Zones

Zone 1 clear
Zone 2 shaded

these estimates is not typical of new residential construction.[25] The average home constructed in Washington is 57 percent larger than this “standard” house. Assuming that energy consumption is directly proportional to square footage, the carbon dioxide reduction estimates in Table 6 were scaled by 1.57.

TABLE 6
**Annual per House Carbon Dioxide Reduction in tons**

| Zone | Natural Gas | Electric |
|---|---|---|
| **Zone 1** | .505 | .134 |
| **Zone 2** | .567 | .187 |

To project the 2010 carbon dioxide benefits of this code upgrade requires estimates of future home construction rates and the proportion of new homes heated with natural gas and electricity. This report assumes 1992 and 1993 residential construction rates continue through 2010 (18,000 units per year in zone 1 and 2400 units per year in zone 2). Also assumed is that 36 percent of new homes will use natural gas heat (the current rate). Based on these assumptions an emission reduction of about 106,000 tons per year in 2010 of carbon dioxide is estimated to result from upgrading the residential energy codes to class 35 windows for new construction (see table B-5). A cost effectiveness estimate was not calculated since the aggregate energy costs savings are greater than the added home construction costs.

**Space Heat In Existing Homes.** Another potentially large source of carbon dioxide emission reductions is improving insulation in existing homes. Nationally, the residential sector has experienced an impressive improvement in energy efficiency; between 1978 and 1990, energy consumption fell by more than 1 quadrillion Btu (Bisio). Over this period the energy intensity of new living space has decreased and many older units were retrofitted with energy saving measures. However, a sizable gap remains between potential and actual energy efficiency. Many of the available energy saving measures are clearly cost-effective (in some cases the pay back period is as short as two years). The 1990 National Energy Strategy and a survey by the Office of Technology Assessment (OTA) offers some insight on why the public has not enthusiastically adopted these measures.

1 Traditional energy rate setting does not reflect the full costs to society of energy use. Thus individual consumers under value energy efficiency investments and renewable resources.

2 Failure of market mechanisms to induce adoption of economical energy saving measures by residential customers, particularly in situations where those who pay for such devices cannot expect any economic benefits.

3 First-cost bias tendency of buyers (especially builders and home buyers) to minimize up front costs of residential property and major appliances.

4 Mortgage lending practices that fail to consider the lower total cost of energy saving homes in calculating mortgage eligibility.

5 Low incomes of some energy users that often make them unable to finance energy efficiency improvements no matter what the payback period.

6 Absence of credible data on reliability and costs of energy saving technologies for builders, architects, utility programs, mortgage lenders, and individual consumers.

[25] This “standard” home is a three bedroom, two bathroom, one-level rambler with 1344 square feet of living space. The Northwest Power Planning Council established this home as the “standard” in the 198_ power plan.

7 Fragmented and cyclical nature of home building industry that contributes to a reluctance to try innovative energy saving designs, products, and construction techniques and makes concerted industry led efficiency initiatives unlikely.

8 Inadequate implementation and enforcement of resources to check actual plans and construction sites and to educate builders.

9 Inadequate energy efficiency investments in public sector housing because many local housing authorities lack funds and management incentives to improve efficiency.

10 Slow turnover of residential structures, heating and cooling systems, and household appliances.

11 Energy costs represent a relatively low proportion of total costs (about 1 percent of salary costs in a typical office).

12 Energy efficiency is often (mis)perceived as requiring sacrifice, limiting its appeal.

The large inventory of homes in Washington, especially those built before the 1970s when building energy codes began and insulation practices became more common (Table 7) provide large opportunities for energy saving measures.

**TABLE 7**

**Existing Homes in Washington State†**

| Year built | Zone 1 | Zone 2 |
|---|---|---|
| 1989 to March 1990 | 40,528 | 1,635 |
| 1985 to 1988 | 116,030 | 8,091 |
| 1980 to 1984 | 115,276 | 11,621 |
| 1970 to 1979 | 224,225 | 38,224 |
| 1960 to 1969 | 186,876 | 16,177 |
| 1950 to 1959 | 127,573 | 26,395 |
| 1940 to 1949 | 87,998 | 16,184 |
| 1939 or earlier | 161,621 | 31,778 |
| **Total** | **1,060,127** | **150,105** |

†From 1990 US Census data

**Existing Electrically Heated Homes.** The Northwest Power Planning Council (NWPPC) prepares a Northwest Conservation and Electric Power Plan at approximately five year intervals. The 1991 Plan analyzed the cost and energy savings potential of several retrofit measures to improve the energy efficiency of existing electrically heated residences (using the "standard" 1344 square feet entry level home). For both zones it is clearly cost effective to insulate the ceiling and crawl space to an R-19 level and exterior walls to an R-11 level (see Table B - 6). These measures are estimated to lower per house carbon dioxide emissions by 17.4 tons in zone 1 and 24.2 tons in zone 2.

Two assumptions are central in estimates of the aggregate emission reductions available from these measures. First, 10 percent of homes built before 1970 are considered retrofit candidates. Second, the model home is thought to reasonably represent older homes which tend to be smaller than the current building practices. Finally, electricity is presumed to heat 50 percent of existing homes in zone 1 and 41 percent of homes in zone 2 (1990 US census data). With the assumptions mentioned above, the carbon dioxide reductions from these retrofit insulation measures are 815,000 tons in 2010 (see Table B - 6). These measures save more money then they cost. Therefore, a cost per ton of carbon dioxide control calculation was not performed.

**Existing Natural Gas Heated Homes.** About the same time the NWPPC studied electrically heated homes, the Washington State Energy Office conducted a study of the potential to reduce energy consumption in homes heated with natural gas (Byers). However, one difference between the two bodies of work was the model home analyzed. The WSEO report modeled a 1600 square foot, single story ranch style home for western Washington [zone 1]. The eastern Washington [zone 2] prototype had 1350 square feet and was modeled with both a full basement and a crawl space.

Updating the energy savings and costs estimates of the WSEO report revealed several cost effective carbon dioxide control measures (see Table B-7). For both zones it is cost effective to install low-flow shower heads and vent dampers, to insulate exterior walls to an R-11 level and floors to an R-19 level (obviously for homes without basements). Additional reasonable measures in zone 2 include insulating ceilings to an R-38 level and duct work. These measures all cost less than $10 per ton of carbon dioxide control and many even save money (including natural gas pipeline capacity savings). On a per house basis, these measures are estimated to lower annual carbon dioxide emissions by 3.1 tons in zone 1 and 3.8 tons in zone 2.

Two assumptions are central in estimates of the aggregate emission reductions available from these measures. First, 10 percent of homes built before 1970 are considered retrofit candidates. Second, the model home is thought to reasonably represent older homes which tend to be smaller than the current building practices. Finally, natural gas is presumed to heat 27 percent of existing homes in zone 1 and 32 percent of homes in zone 2 (1990 US census data). With the assumptions mentioned above, the carbon dioxide reductions from these retrofit insulation measures are 81,000 tons in 2010 (see Table B-8). Like the retrofit measures for existing electrically heated homes, these measures save more money then they cost. Therefore, a cost per ton of carbon dioxide control calculation was not performed.

**New Consumer Appliances.** Improving the energy efficiency of new consumer appliances to reduce greenhouse gas emissions is one area unlikely to need additional effort by the state. As stated above, the federal Energy Policy and Conservation Act and its amendments established efficiency standards for several appliance categories and directs DOE to periodically review and revise those standards as appropriate. These federal appliance efficiency efforts are projected to reduce overall residential electricity demand by 18 percent and natural gas consumption by 13 percent (Ciliano). Based on these reductions, by the year 2010, this program is projected to annually lower green house gas emissions by 1.8 million tons in Washington state.

**Direct Use Of Natural Gas.** Another means to reduce carbon dioxide emissions is to use energy in the most thermodynamically efficient way possible. Directly using natural gas for space and/or water heat rather than in a combustion turbine to supply electricity for space and water heat improves thermodynamic efficiency. The energy content of electricity delivered to a home from a combined cycle combustion turbine is only about 45 percent of natural gas fuel. In contrast, a home furnace typically uses 80 percent of the energy in natural gas to heat the residence.[26] Converting existing homes to natural gas space and/or water heat is usually referred to as "fuel conversion."

To determine the potential for fuel conversion, one must compare the economic costs of both natural gas and electric power—the original fuel source, transmission cost and conversion losses—to produce hot water or temperature controlled space heat. A NWPPC study (1994) found that natural gas could cost-effectively displace the need for about 700 megawatts of electricity by

[26] To be fair, other considerations are also important such as the efficiency at which electricity is converted to useful home heat, duct and flue losses of natural gas systems, characteristics of the heat desired and the energy needed to bring the natural gas to the home.

2010 and lower natural gas use by 6 to 8 trillion Btu per year. Such a change would lower the region's carbon dioxide emissions 360,000 to 480,000 tons per year. Washington state accounts for about 60 percent of this reduction, or 215,000 to 290,000 tons.

Presently, a fair amount of fuel conversion is already taking place due to perceived price/quality benefits. State encouragement of additional conversion would necessarily entail a political decision to favor the natural gas industry over the electric industry. This encouragement could be direct such as regulatory mandates or more subtle such as tax breaks for conversion expenses.

***Current Fuel Conversion***

A BPA survey of the region (Oregon, Washington, Idaho) indicate that about 28,000 single family homes switched to natural gas heating fuel from electricity in 1992. Western Washington and Oregon accounted for 77 percent of the reported conversions.

In a 1992 survey, the Association of Northwest Gas Utilities in cooperation with NWPPC found 15,000 conversion of space heat, 19,000 conversions of water heat for a total of almost 27,000 new gas conversion customers.

**Residential Lighting.** According to the NWPPC, lighting accounts for about 5 percent of the residential sector's electricity use. Region wide this amounted to 290 aMW in 1989; Washington state demand amounts to about 175 average megawatts. Compact fluorescent bulbs use about 25 percent of the electricity of incandescent lights. State demand could fall by as much as 130 megawatts with a fluorescent for incandescent bulb replacement program. (Losing the secondary heat effect of incandescent bulbs somewhat increases space heat energy needs and decrease space cooling energy needs.) This translates in to a potential greenhouse gas emission reduction of 460,000 tons per year.

Some of this potential reduction will not be realized as it is not cost effective to install expensive fluorescent bulbs for limited use. Lesser concluded that utilization rates must exceed 5 hours per day for fluorescent bulbs to yield positive net benefits from a consumers' perspective. However, from a societal perspective (includes the benefits of reducing pollution and long-term avoided costs of new generating resources) Lesser found fluorescent bulbs cost effective at usage levels as little as 1.2 hours per day. This disconnect between consumer and societal benefits provides an opportunity for policy efforts to promote the fluorescent bulbs.

A number of program's around the county attempt to induce a demand for residential fluorescent lighting products. Madison Gas and Electric established its residential lighting program in 1990. Madison's goals were many: to educate and motivate customers to purchase high-efficiency lighting products, to create a stable demand for energy efficient products, to support rather than compete with local business, and to achieve the maximum energy savings at the lowest possible cost. Madison gave customers coupons to use at participating stores to purchase energy efficient products at discount prices. After a year of relatively high start-up costs, the cost of this program is on the order of 30 mills per kWh (The Results Center)—similar to the marginal cost of new generation.

The Burlington Electric Department, a municipal utility in Burlington Vermont, operates another interesting program. The "Smartlight" program leases customers compact fluorescent lamps at a cost of $0.20 per bulb per month. Returning the bulbs in any condition (e.g., broken or burned out bulbs or simply customer dissatisfaction) terminates the lease. The program also allows customers a two month break-in period before lease fees start. Burlington found this "break-in" to be an important promotional option giving customers time to assess the quality of fluorescent light. After three years, 2,375 customers had signed up for the "Smartlight" program. They annually save 108,000 kWh of electricity. Assuming a marginal price for electricity at 0.035 per kWh, this program cost about $750 per ton of carbon dioxide control. However, one would expect considerable economies of scale with this program; the cost effectiveness should improve with increased participation.

It is difficult at this point to estimate the emission reduction potential or cost-effectiveness of a fluorescent light promotion program. Much depends on how the program is run and who it targets. Generally speaking high cost is the largest obstacle to wide-spread use of fluorescent lights. Efforts to reduce these costs to consumers significantly affect compact fluorescent bulb penetration and use.

**Geothermal Heat Pumps.** Geothermal energy is one of the cleaner forms of energy available in commercial quantities. In terms of climate change, the benefit of geothermal is that it displaces technologies that emit greenhouse gases. Geothermal energy provides an enormous resource for low-temperature applications such as space heating and cooling in residential and commercial structures.

For the residential sector, geothermal energy is typically extracted with ground source heat pumps and is used for space heating. According to Reed the need for electrical generation capacity is reduced by 2 to 5 kW for each residential installation of a ground source heat pump. Assuming a 30 percent capacity demand factor for electricity, ground source heat pumps should annually reduce per house electricity demand by 5,250 to 13,140 kWhs.

A program to that equips 10 percent of all new homes in Washington with ground source heat pumps would lower electricity demand by 323,062 to 129,225 MWhs in the year 2010. As a result, carbon dioxide emissions would fall 130,000 to 52,000 tons.

An absence of information on the cost of ground source heat pumps prevented estimating the cost-effectiveness of this measure as a means to reduce greenhouse gas emissions. However, the U.S. General Accounting Office (GAO) reports that *"in most parts of the country… [ground source heat pumps] offer homeowners and building owners the lowest life-cycle cost for heating and cooling."* Despite this advantage, ground source heat pumps command less than one-half of one percent of the space conditioning market. To expand market share GAO recommends: programs to educate the public about ground source heat pumps; efforts to reduce installation costs; and state and utility conservation programs that promote greater use of energy-efficient technologies.

***Ground Source Heat Pumps***

Heat pumps in general are highly efficient since they "transfer" heat rather than "create" heat from a combustion process. Ground source heat pumps enjoy extra advantage of stable source/sink temperatures (the ground). In the Pacific Northwest, temperatures of the ground stay within a few degrees of 55°F throughout the year. Ground source heat pumps use this temperature reservoir as a heat source during winter heating and a heat sink during summer cooling. As a result, ground source heat pumps use 23 to 44 percent less electricity than their air-coupled cousins and 63 to 72 percent less electricity compared to electric resistance heating (Reed). Further, Gilli concludes that application of heat pumps where economic could reduce global $CO_2$ emissions by 4.2 percent.

## The Commercial Sector

Washington State's commercial sector is projected to annually release over 9 million tons of carbon dioxide by 2010. Almost 85 percent of these emissions result from electricity and natural gas consumption. Technology improvements and building efficiency codes will help to limit emissions somewhat. However, considerable potential remains to further reduce commercial energy consumption and thereby reduce greenhouse gas emissions.

Unfortunately, sector wide estimates of greenhouse gas reduction potential is problematic due to a wide variety of building types[27] and a paucity of information about how efficiently they use energy. Therefore, this report uses national estimates of energy end-uses and efficiencies to estimate potential carbon dioxide emission reductions. Table 8 presents estimates of the potential energy savings from efficiency improvements for several energy end-uses. The energy efficiency measures come from the OTA report Building Energy Efficiency and are ascribed to have saved more money in reduced energy expenditures than they cost. However, a lack of cost data prevents detailed cost-effectiveness calculations.

TABLE 8
**Energy Consumption by End Use†**

| Energy End Use | Proportion of Total Energy Use | Energy Use | Potential Energy Reduction | Reduction in Carbon Dioxide Emissions |
|---|---|---|---|---|
| | | quads | percent | millions of tons |
| Space Heating | 0.32 | 0.1296 | ? | |
| Lighting | 0.28 | 0.1134 | 40 | 5.40 |
| Space Cooling | 0.16 | 0.0648 | ? | |
| Food Storage | 0.5 | 0.0203 | 23 | 0.55 |
| Water Heating | 0.4 | 0.0162 | ? | |
| Other | 0.15 | 0.0608 | ? | |

† 1988 national energy use averages and potential energy improvement estimates from Building Energy Efficiency, OTA, 1992. Given the mild summers typical of the Pacific Northwest it is likely that Washington has a lower space cooling energy expenditure than the national average. Assume a 2010 Commercial sector energy consumption of 0.405 quadrillion Btu (from Supplement to Annual Energy Outlook, 1993, Energy Information Agency). Carbon dioxide reduction estimates assume that the energy savings displace electricity from a natural gas fired combustion turbine rather than a hydro electric dam.

**Space Conditioning** needs in commercial buildings is usually load dominated, meaning that it arises as a result of activity within the building rather than from ambient conditions outside the structure. Unfortunately, the diversity of buildings makes it difficult to generalize about the energy savings potential. Therefore, specific energy improvements were not assessed. Types of activities that can improve commercial building space conditioning efficiencies include:

- improved efficiency of energy-using devices (OTA reports that the typical commercial gas furnace is about 70 percent efficient while newer high-efficiency units achieve 90 percent efficiency)
- improved system design and system controls;
- switching to a more efficient system (a heat pump rather than electric resistance heat);
- improved system maintenance; and
- reduced internal system “loads” (e.g., switching to fluorescent lights to lower the need for space cooling).

**Lighting** consumes about 41 percent of the commercial sector electricity load (28 percent of total energy load). The opportunities for improved lighting efficiency are considerable. Commercially available technologies could lower lighting electrical use 40 percent. Other

[27] **Energy Consumption of Different Commercial Building Types†**

| Building Type | Proportion of Energy Use | Building Type | Proportion of Energy Use |
|---|---|---|---|
| Office | 23 | Food | 9 |
| Retail/Service | 21 | Assembly | 9 |
| Warehouse | 10 | Health Care | 7 |
| Education | 10 | | |

† From Building Energy Efficiency, OTA, 1992.

potential efficiencies improvements include: fluorescent lamps (~15 percent), ballasts (20-25 percent), lighting fixtures (up to 50 percent) and lighting controls switches(~20 percent).

**Commercial Food Refrigeration** systems move heat from one place to another. Energy efficiency opportunities include reducing the amount of heat to be moved. Plastic strips on supermarket refrigerated display cases reduce energy use 15 to 45 percent, for example. Glass doors lower energy use 30 to 60 percent. Improvements to the refrigeration system offers large energy savings. Multiple compressors in parallel reduce energy use 13 to 27 percent. Tuning the compressor pressure to ambient conditions (rather than for the hottest day) lowers energy demand by over 20 percent. Variable speed drives for the compressors also save energy. Heat recovery devises which capture waste heat from refrigeration system for use as space heat also improve efficiency. One side-by-side test of conventional and advanced commercial refrigeration systems revealed a 23 percent energy savings for the advanced system.

**Water Heating** The methods and systems used for heating water in commercial buildings vary widely as do the options for efficiency improvements. Demand reductions include leak repair, restrictors and reduced temperature settings. System retrofits include tank insulation, electronic ignition, electric flue dampers and boiler tune-ups. New commercial water heating technologies include the use of heat pumps, heat recovery devices, and other methods for integrating water heating into other heating and cooling systems. The overall energy efficiency improvement resulting from such changes is uncertain.

**Incentives for Energy Efficiency** One innovative commercial sector DSM program is run by the Public Service Electric and Gas Company (PSG&E) of New Jersey which pays participants for energy savings based on utility time-of-day and seasonal costs. The primary objective of the Standard Offer program is to avoid the need for new power plant capacity. To participate, the commercial entity must save 100 kW of electricity during the “Summer Prime Period” and/or 25,000 therms of natural gas during the peak gas period. The Standard Offer contract also includes penalties for failure to produce the promised energy savings by the agreed to timeline. The basic mechanism to participate in the Standard Offer Program is as follows:

- **Initial Commitment:** A customer commits to specific energy savings for a certain number of years.
- **Project Qualification:** A third-party analyzes the facility’s operating characteristics and proposed efficiency measures to ensure the Standard Offer project is technically and economically feasible.
- **Investment Grade Inventory:** A detailed inventory of customer facilities is performed to comprehensively identify existing energy-consuming equipment and to recommend specific efficiency measures. This inventory outlines the costs, revenues, and energy savings of the project. Results of the inventory serve as a basis to evaluate the project’s energy savings on an ongoing basis.
- **Proposal to PSE&G:** A proposal is submitted to the utility outlining the project key elements and scope of work. This proposal includes a daily and seasonal schedule of energy savings.
- **PSE&G Sign Off:** Once PSE&G accepts a project proposal, the seller of savings executes a Standard Offer energy savings agreement with PSE&G. Contract terms are 5, 10, or 15 years.
- **Construction:** The seller installs the new efficiency equipment. The seller notifies PSE&G when construction is 50% complete. Upon completion, the seller submits a report to PSE&G describing the installation and any deviations from the original project proposal. The seller also performs a post-implementation audit, which includes a visual inspection of all areas and systems associated with the project, and measurement of the power of a representative sample of circuits.
- **Ongoing Obligations:** Savings are monitored on a regular basis to ensure that contract terms are met. The seller bills PSE&G for energy savings on a monthly basis. All obligations of the seller extend for the life of the Standard Offer Contract. An increase or decrease in the hours of operation

results in higher or lower payments from PSE&G. However, there are some limitations and payment restrictions for increased hours and some penalties for decreased hours.

- **Utility Fees:** The party selling energy savings to PSE&G pays certain fees to the utility, including audit fees; a $1/kW fee when a proposal is submitted, a damage deposit at around $70/kW to ensure a project is completed on schedule; and monthly administrative fees.
- **Ongoing Auditing:** Throughout the development and following completion of a Standard Offer project, ongoing energy savings measurement and verification is required of the seller. PSE&G may send auditors on site to monitor its progress. The first audit is performed once a proposal is submitted and sets the baseline of pre-construction. Auditors verify compliance with the project proposal and determine the new energy consumption levels. If savings fall below contract specified levels, PSE&G reduces the payments to the seller and may assess additional penalties.

The goal of the standard offer program is to save 60-70 MW of electricity. PSE&G has not established specific goals for natural gas savings. Total annual savings for the program through December 15, 1994 are 58.5 MW and 209,800 MWh. The annualized cost to the utility of projects approved by the utility is nearly $10 million. Assuming the program saves 60 MW per year over a six-year period, the utility would save approximately $600 million.[28]

**Public Sector Commercial Buildings.** A subset of commercial buildings are those owned and operated by the public sector. Under contract to the WSEO, Ecotope assessed the potential for improving the energy efficiency of the many types of public buildings. The results of that study are presented in Table 9. The last column presents estimates of the carbon dioxide reduction available from each facility type. In all cases the efficiency measures pay for themselves through reduced energy expenditures. Therefore, a cost-effectiveness of carbon dioxide control was not calculated. Complete implementation of all cost effective measures identified by Ecotope is estimated to lower carbon dioxide emissions by almost 0.44 million tons in 2010.

The conservation measures analyzed included lighting (the use of more efficient light equipment and controls that reduce hours of operation), heating, ventilating and air conditioning systems (improved efficiency systems, improved controls and operation), building envelope (install higher insulating windows), and improved appliances (low-flow faucets).

**TABLE 9**

**Estimated Carbon Dioxide Reduction Potential From Public Sector Facilities†**

| Facility Type | Square Feet | Annual Energy Savings | | Cost | Carbon Dioxide Reduction |
|---|---|---|---|---|---|
| | millions | MWh | Therms | millions of $ | tons |
| Office | 24.4 | 149.7 | 46.9 | 32.7 | 64,381 |
| Schools | 129.0 | 307.8 | 1299.5 | 72.4 | 228,619 |
| Residential | 10.7 | 31.5 | 266.7 | 9.2 | 34,094 |
| Health Care | 7.5 | 35.0 | 433.4 | 8.0 | 48,847 |
| Recreation and Parks | 7.0 | 44.3 | 148.0 | 8.4 | 29,782 |
| Jails/Prisons | 6.9 | 34.8 | (190.1) | 8.4 | (1,114) |
| Storage | 5.3 | 3.2 | 6.1 | 0.6 | 1,784 |
| Warehouse and Shop | 25.9 | 10.8 | -- | 1.6 | 4,374 |
| Water and Wastewater | 0.9 | 65.1 | 7.4 | 14.5 | 26,958 |
| **Total** | | **682.2** | **2017.9** | **155.8** | **437,723** |

† Energy Conservation in Public Buildings, Ecotope, 1990

## The Industrial Sector

[28] The costs and energy savings estimates are from Public Service Electric & Gas, Standard Offer Program, The Results Center, Number 96. These numbers have not been verified by independent analysis.

The Industrial sector is a significant source of carbon dioxide in Washington State. The industrial sector released an estimated 18.3 million tons of carbon dioxide equivalent in 1990 and is projected to emit 24.1 million tons in 2010. This sector provides broad opportunities to reduce greenhouse gas emissions. However, few industry wide greenhouse gas control programs are available due to the diverse nature of industrial activities and differences in production techniques, processes and fuels used within the same industry. Moreover, the current state of industrial energy efficiency in Washington is far from certain. Given these problems this report follows two tacks. First, efficiency improvements identified by the NWPPC in its preparation of the upcoming Northwest Conservation and Electric Power Plan are described. Then this report considers efficiency improvement measures available for certain large industries.

**Industrial Electricity Efficiencies Identified By The Northwest Power Planning Council.** In preparation for the upcoming plan the NWPPC estimated the amount of cost-effective conservation energy savings available from the industrial sector. The energy savings estimates for ten large conservation measures are listed in Table 10. Implementation of these measures is estimated to reduce regional electricity demand by approximately 830 average MW of which about 500 MW is located in Washington state.[29] These savings would reduce annual carbon dioxide emissions by some 1,764,000 tons in Washington and reduce costs to industry.

**TABLE 10**
**Electricity Energy Savings Potential in the Industrial Sector†**

| Conservation Item | Cost (mills) | Energy Savings (aMW) |
|---|---|---|
| Replace inlet vanes on air drying fans with a variable speed | 18 | 6 |
| Downsize motor to better match load | 6 | 24 |
| Install unloading valve and accumulator for hydraulic pumps | 2.1 | 27 |
| Replace fluorescent lamps with high-efficiency fluorescent lamps (e.g., 75 watt to 60 watt) | 23 | 28 |
| Install an electronic variable speed drive to better control motors subject to varying load conditions (5-20 hp) | 18 | 31 |
| Install variable speed drive to replace throttling device to correct for pump over capacity | 10 | 34 |
| Equip air compressors with unloading kites to reduce demand during idle periods. | 1.4 | 39 |
| Install an electronic variable speed drive to better control motors subject to varying load conditions (21-50 hp) | 15 | 44 |
| Install oversize piping to lower friction/pressure losses | 33 | 64 |
| Install an electronic variable speed drive to better control motors subject to varying load conditions (51-125 hp) | 14 | 111 |
| Downsize pumps to better match loads (e.g., from 10 to 5 hp) | 4 | 117 |
| Install an electronic variable speed drive to better control motors | 3 | 308 |
| **Total** | | **833** |

†From the NWPPC Industrial subcommittee, Conservation ResourceAdvisory Committee

[29] According to BPA sales data, Washington accounts for about 60 percent of the regional electricity demand. 60 percent of 830 MW is approximately 500 MW. More recent NWPPC estimates target 500 MW of conservation from the industrial sector. All t this conservation costs less than $0.025 per kWh and a significant portion comes in at less than $0.010 per kWh.

As stated above, estimating the energy efficiency improvement potential for Washington's industrial sector is extraordinarily difficult. The energy consumption of various industrial sectors is not known nor is data available on the current state of energy efficiency. To establish baseline energy consumption levels for various industrial sectors, NWPPC projections for 2010 industrial electricity consumption (medium estimate) were melded with data from the 1982 census of industrial energy use. Further, efficiencies of Washington industries were assumed comparable to current national averages. The accuracy of these data and assumptions are questionable and therefore the carbon dioxide reduction estimates should be considered preliminary.

***Industrial Energy Efficiency***

U.S. industries have greatly improved their energy efficiency. Industrial sector energy consumption declined 10 percent Between 1973 and 1990, concurrent with a 30 percent growth in output. New equipment usually has an efficiency advantage over old equipment. Therefore, replacing old or obsolete equipment generally improves efficiency. Even absent major public policy changes, OTA predicts a 1.2 percent annual gain in industrial efficiency,

**Petroleum Refining** On average about 600,000 Btu are used to process a barrel of crude oil into its various products.[30] The most energy intensive steps are the reorganization and distillation processes while the largest energy loss in the refining process occurs during final cooling of process streams. Where feasible, the low-level heat is transferred to other process streams. The opportunities for recovering significant amounts of low-level heat are much greater in facilities designed to optimize heat recovery. Process heaters and steam boilers also offer opportunities for reducing energy use.

Distillation is the primary process for breaking down crude oil into its constituent hydrocarbons. Crude oil is fed into heated distillation columns where the lighter hydrocarbons vaporize and are removed. Light end fractions such as propane and butane come off the top, Napthas, kerosene, heating oil, diesel fuel, and heavy gas oil are tapped successively lower on the distillation column. Heavy products that do not vaporize are removed from the bottom of the column. Separation accounts for 23 percent of the energy used in refining. State-of the art technologies such as vapor recompression, staged crude preheating, and air condensers can reduce energy use in distillation by 55 percent.

Hydrocarbon cracking is used to convert heavier, low value hydrocarbons into lighter high value ones. Cracking—breaking apart the hydrocarbon chains to decrease their size—is carried out by catalytic processes (to produce gasoline), hydrocracking processes (to produce gasoline and aviation jet fuel) and thermal processes (to process low-grade residual oils). Cracking accounts for 13 percent of the energy used in refining. State-of-the-art technologies such as fluid coking to gasification, mechanical vacuum pumps, and hydraulic turbine power recovery can reduce conversion energy use by about 16 percent.

Two other areas of crude oil processing offer little potential for improved efficiency. Finishing, 17 percent of energy consumption, removes detrimental components from petroleum products. Reforming, 29 percent of energy used in refining, raises octane levels.

Adoption of currently available state-of-the-art technologies can reduce energy consumption in the petroleum sector by about one-third; to about 400,000 Btu per barrel of crude oil. Overall, the 2010 energy consumption by the petroleum refining industry in Washington is estimated at 990 million kWh of electricity and 10,300 million Btu of fossil fuels. Assuming efficiency

[30] The information on the energy efficiency improvement potential of petroleum refining, pulp and paper, aluminum production, Portland cement manufacturing and glass making came from an OTA report Industrial Energy Efficiency.

improvements decrease these energy levels by 33 percent, carbon dioxide emissions would fall by 133,900 tons. Unfortunately, information on how much these technologies cost is lacking. Therefore, a carbon dioxide reduction cost effectiveness was not estimated for this industry.

**Pulp And Paper** Paper mills process cellulose fibers into paper products. There are five principle steps in paper production: wood preparation; pulping, bleaching, chemical recovery and paper making. On average about 35 million Btu are used to produce a ton of paper. Wood preparation uses relatively little energy while pulping is energy intensive. Pulping breaks apart the wood fibers and removes unwanted wood residues using either mechanical or chemical processes. State-of-the-art pulping technologies such as continuous digestors, displacement heating, anthraquinone pulping, and thermomechanical pulping with heat recovery can reduce the energy use of this stage by about 26 percent from current average practices.

Bleaching whitens the pulps by altering and/or removing lignin, which causes the dark color of pulp. Bleaching uses about 7 percent of the energy used in paper production. Sate-of-the-art technologies such as displacement bleaching can reduce the energy use at this stage by 30 percent. Many paper making processes use chemicals to separate cellulose fibers. Regenerating these chemicals for reuse is important for economic and waste disposal reasons. Chemical recovery accounts for about 19 percent of the energy consumption. Sate-of-the-art technologies such as displacement bleaching can reduce the energy use at this stage by about 37 percent.

Paper making is generally the last stage of paper production. It includes stock preparation, sheet forming, pressing and drying. Paper production consumes large quantities of energy; about 38 percent of the energy used in paper making. Drying and stock preparation are the most energy-intensive activities. State-of-the-art technologies such as top-wire formers and improved mechanical and thermal water removal techniques can reduce the energy use of this stage by about 32 percent.

Adoption of state-of the-art technologies in the pulp and paper industry would reduce energy consumption by 29 percent from current average practices. Energy consumption by the pulp and paper industry is projected at 8,921 million kWh of electricity and 54,300 million Btu of fossil fuels in 2010. Assuming efficiency improvements decrease these energy levels 29 percent, carbon dioxide emissions would fall by 1,049,000 tons. Again, no information on how much these technologies might cost was found, so a carbon dioxide reduction cost effectiveness was not estimated for this industry.

**Aluminum Production** Aluminum refining requires removing the oxygen from alumina ($Al_2O_3$). To accomplish this, the alumina is dissolved in molten cryolite ($Na_3AlF_6$) in carbon lined pots. An electrical current passed between carbon electrodes in the pot reduces the alumna to aluminum. Smelting consumes about 65 percent of the energy used in aluminum production. Current average smelting efficiency is about 7.3 kWh/lb. of aluminum. State-of-the-art smelters use 6.0 to 6.5 kWh/lb., an 11 to 18 percent improvement. (Another way to reduce energy consumption is to increase the use of recycled aluminum. Recycling requires only about 5 percent of the energy needed to produce primary aluminum from bauxite. Recycling accounts for about one-third of U.S. aluminum production.)

Aluminum production is projected to continue to consume prodigious amounts of energy in Washington - 18,266 million kWh of electricity and 15,200 million Btu of fossil fuels per year. Adoption of state-of the-art technologies in the aluminum industry would reduce energy consumption by 16 percent from current average practices. Such savings would lower carbon dioxide emissions resulting from this industrial sector by 1,183,800 tons. However, we have no information on how much these technologies might cost so we cannot estimate a cost effectiveness of carbon dioxide reduction for the aluminum industry.[31]

**Portland Cement** is the bonding agent that holds aggregate and sand together to form concrete. The raw materials for Portland cement are limestone, silica sand, alumina and iron ore. These materials are crushed and mixed together, and then burned at high temperatures ≈ 2,800°F. This sinters and partially fusses the materials in marble-sized pellets known as clinker. The clinker is ground into a powder and mixed with gypsum. The main processes involved with Portland cement manufacture are raw materials preparation, clinker production and finish grinding.

Raw materials preparation accounts for about 8 percent of the energy used to produce Portland cement. This step includes crushing, proportioning, drying, grinding, and blending the input materials. Energy efficient technologies could reduce the energy use in this step by about 19 percent. Clinker production is the most energy intensive part of making Portland cement accounting for some 80 percent of energy use. State-of-the-art technologies, such as the dry process with either preheat or precalcine and improvements in kiln refractories, kiln combustion and improved cooling techniques are estimated to reduce energy use in clinker production by about 26 percent from current average practices.

Grinding the clinker into a fine powder accounts for 11 percent of the energy use in cement production. State-of-the-art technologies, such as pre-grinding and improved classification techniques are estimated to reduce energy use in finish grinding by about 28 percent from current average practices. Overall, state-of-the-art technologies could reduce energy use some 28 percent in the Portland cement industry. Information on the cost of these technologies was not uncovered so no carbon dioxide reduction cost effectiveness estimate is presented.

**Glass** is used to make a variety of products including: windows, windshields, jars, light bulbs, tableware, and fiberglass. The energy used to manufacture a ton of glass averages between 15 and 27 million Btu depending on the final product. The major categories of glass making are batch preparation, melting and refining, forming and post-forming.

Glass making begins with weighing and mixing raw materials (recycled material is crushed and added at this stage). Batch preparation accounts for about 4 percent of the energy used in glass production. Computer controls for weighing, mixing, and charging saves about 10 percent of the energy used in this step. The next step in glass manufacture is melting the raw materials in furnaces heated to 2,400 and 2,900 °F. Glass is produced in a variety of furnaces including, regenerative, recuperative, electric, and pot. Melting and refining account for 50 to 68 percent of the energy used to make glass. State-of-the-art technologies such as oxygen-enriched combustion air, improved process control and better refractories can reduce the energy consumption at this stage by an estimated 8 to 37 percent.

In glass forming, molten glass is homogenized and heat conditioned. The forming stage differs depending on the product to be produced. Forming accounts for 12 to 33 percent of the energy

---

[31] The carbon dioxide reduction estimates assume that the reduced energy consumption offsets the need for electricity produced by a combustion turbine. Should the energy savings result in less hydroelectic generation, the carbon dioxide reduction would be zero. Note that the carbon dioxide emissions for the aluminum estimated by Kerstetter for the Washington State inventory only include greenhouse gases emitted as a result of the manufacturing process. For example, the chemical process to produce aluminum is as follows: $2Al_2O_3 + 32C \rightarrow 4Al + 3CO_2$. Any carbon dioxide emitted as a result of supplying electricity to the aluminum industry was not included in the Kerstetter estimate.

used in glass production. State-of-the-art forming technologies can reduce the energy used at this stage by an estimated 10 to 20 percent. After it is formed additional postforming processes are sometimes used to adjust the strength and other properties of the glass. Post forming accounts for 11 to 18 percent of the energy used in glass production. State-of-the-art post-forming technologies can save 11 to 28 percent of the energy relative to current practices.

State-of-the-art technologies could reduce energy consumption by 32 percent for flat glass production, 22 percent for container glass, 17 percent for pressed and blown glass, and 12 percent for fibrous glass from current average practices in the glass industry. Information on the cost of these technologies is not available so the cost effectiveness estimate was not calculated. Together, the Portland cement and glass industries are estimated to consume 510 million kWh of electricity and 7,100 million Btu of fossil fuel. And together the carbon dioxide reduction resulting from adopting state-of-the-art technologies is about 52,174 tons.

**Recycling** Washington state generates approximately 5.7 million tons of municipal solid waste each year, or about 6.4 pounds per person per day. Nearly 34 percent of this waste is recycled—the highest recycling rate in the nation. To further promote recycling, Washington set a goal of recycling 50 percent of its waste stream (The Solid Waste Management—Reduction and Recycling Act, RCW 70.95). Recycling offers industrial entities further opportunities to reduce energy consumption and carbon dioxide emissions. The energy savings expected to accrue as a result of achieving the 50 percent recycling goal are shown in Table 11. Note that these are incremental savings of improving on current recycling levels.

As can be seen from this table, recycling of some materials results in greater benefits than recycling of others. In particular, metal recycling produces large energy benefits. On the other hand, glass recycling is almost as energy intensive as production. Recycling plastic saves energy in the forms of oil and gas and is therefore desirable. Paper recycling must be divided into Kraft and newsprint. Newsprint recycling saves trees and fossil fuels while recycling Kraft paper appears to save little energy. A life-cycle analysis for Kraft paper that includes production from dedicated plantations (to save old-growth forests) and paper combustion for energy recovery would minimize fossil fuel use as will as landfill volume (Gaines and Stodolsky).

**TABLE 11**

**Energy Savings from Recycling**

| Commodity | Recycling Rates, 1990† | Discard Amounts, 1992† (tons) | Recycling needed to meet 50 % goal (tons) | Energy Saved by Recycling (MBtu/ton)‡ | Energy Saved by Achieving 50% Recycling Goal (MBtu) |
|---|---|---|---|---|---|
| Glass | 0.298 | 183,546 | 52,815 | 2 | 105,630 |
| PET | 0.053 | 14,335 | 6,766 | 66 | 446,556 |
| HDPE | 0.047 | 29,270 | 13,913 | 66 | 918,258 |
| Other Plastics | 0.055 | 359,712 | 169,388 | 49 | 8,300,012 |
| Aluminum Packaging | 0.632 | 30,439 | | 154 | 0 |
| Tin Cans (steel) | 0.175 | 59,131 | 23,294 | 12 | 279,528 |
| Kraft and Other Paper | 0.500 | 710,808 | 0 | 0 | 0 |
| Newsprint | 0.444 | 160,960 | 16,212 | 12.2 | 197,786 |
| | | | | **Total** | **10,247,770** |

† From Municipal Solid Waste in the Pacific Northwest, The Washington State Energy Office, WSEO 93-190.

‡ From Mandate Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume (Gaines).

To achieve these high recycling levels, effort is needed to overcome technical and institutional barriers. High recycling rates require either separation of mixed waste at a central facility, or improved source-separation procedures. Further, clean and easy to handle waste products are probably already being recovered. Therefore, declines in material quality and increased recovery costs will likely accompany an increase in recovery rates. Eventually, a break-even point will be reached at which the benefits of additional recycling are outweighed by the extra cost. This analysis does not attempt to identify this point, nor does it estimate the costs of increased recycling rates to 50 percent. However, the energy necessary to collect sort and pre-process recycled materials lowers the above energy savings estimates by about 8 percent. The net energy savings from achieving a 50 percent recycle rate totals 9,248,000 MBtu. This translates into a carbon dioxide emission reduction of 1.05 million tons per year.

It is clear from this analysis that the optimal recycling rate is not the same for every material. Glass, for example, has a small energy benefit from recycling as does Kraft paper. On the other end of the spectrum, aluminum generates more than half of the energy benefits from recycling even though it makes up only a small portion of the total waste stream. As such, to achieve the largest energy benefit, the state should concentrate its recycling efforts towards aluminum and plastic. Of course other factors like land fill space influence recycling decisions. For example, a trade-off between trees and fossil fuels is important to the Kraft paper recycling decision. Clearly defined objectives are necessary for decision makers to establish appropriate recycling goals. Finally, the option to reuse which is often overlooked, may be the best option for many plastic and glass containers. The limits of public cooperation in this area need to be explored through bottle deposits and other programs.

## The Transportation Sector

The transportation sector is the largest source category for carbon dioxide emissions, resulting in approximately 46 million tons in 1990 and projected at 66 million tons in 2010. An effective greenhouse gas control program must achieve substantial reductions in this sector. However, it will be difficult. Americans highly value the attributes of owning and operating motor cars. As a Swedish official observed (Kempton)

> *"[Global warming is] a tough political problem. At its roots are the dependence of society and its people on the cars, and the symbolic value that the car has to anyone. That's synonymous with industrial development and all the good that this has done… the freedom that this has created for ordinary people … It's representing the good life of an industrial society. Doing anything to that, that's killing yourself practically and politically.… [I] believe that is one of the reasons why, from the political side, one would hesitate in taking very strong actions…"*

Emission reduction strategies for the transportation sector fall into four principal categories:

- Improving the fuel efficiency of new motor vehicles;
- Improving the fuel efficiency of motor vehicles in-use;
- Shifting to alternative fuels; and
- Modifying demand (trip length, load factors, and travel modes).

### New Motor Vehicle Fuel Efficiency

The federal government is the sole regulator of motor vehicle fuel efficiency. Federal statutes prohibit the States from establishing motor vehicle efficiency standards. Federal regulation began in 1976 through Corporate Average Fuel Efficiency (CAFE) standards. When the CAFE standards first went into effect, new vehicle average fuel efficiency was 17.2 miles per gallon (mpg). That figure rose 10 mpg over the next ten years. Fuel efficiency levels have since stabilized at around 28 mpg.[32] Proponents of fuel efficiency standards argue that currently available technologies could markedly improve motor vehicle efficiency. Indeed, the Congressional OTA reports that regulatory pressure could raise average new car fuel efficiency by about 13 percent in 2000 and 22 percent by 2005.

***Elasticity***

Elasticity measures consumer response to changes in price. A price elasticity of -0.7 indicates that a 10 percent increase in price, reduces consumption by 7 percent. The elasticity of fuel efficiency of 0.32 indicates that consumers purchase vehicles with a 3.2 percent higher mileage rate when gasoline prices rise 10 percent.

In an attempt to capture some of these efficiencies, the Administration launched the "Partnership for a New Generation of Vehicles." One goal of this partnership is to achieve fuel efficiency improvements of up to three times the average of Concorde/Taurus/Lumina, with equivalent customer purchase price of today's comparable sedans by 2004. According to the Partnership, technologies with the potential to meet program goals include: high-speed diesel engines (which includes the development of $NO_x$ reduction catalysts and particulate traps; fuel cells, provided cost, size, weight and fuel supply system difficulties are corrected; and, electric vehicles, though battery technology in not expected to develop quickly enough to meet the partnership time frame. Non-powertrain developments include: lightweight body and chassis materials (e.g., aluminum, magnesium, metal matrix composites, high-strength steel, polymer and polymer matrix composites) and improved design techniques (e.g., crash energy management, structural design, and reduced aerodynamics, rolling resistance and accessory loads). While this partnership may dramatically improve motor vehicle fuel efficiency, the federal preemption of state mandated fuel efficiency standards precludes their further consideration here. However, there are other avenues to improve motor vehicle fuel efficiency.

**Gasoline Tax.** The cost of motor vehicle travel borne by commuters (gasoline, insurance, vehicle wear and tear) is only part of the cost to society. Other social costs, such as congestion and environmental degradation, are not directly seen as personal costs by commuters. These costs are estimated at over $0.10 per mile (Cameron). A gasoline tax exposes more of the actual costs of driving to the commuter. Over the long-run commuters would respond to higher fuel prices in two ways; they acquire more fuel efficient vehicles and adopt behaviors which lower transportation demand, such as moving closer to work or using alternatives to single occupancy vehicles.

***Economic Consequences of a National Gasoline Tax***

Brinner et. al. examined the economic effects of a national gasoline tax designed to stabilized transportation greenhouse gas emissions ($0.45 per gallon in 2000 and $1.30 by 2010). Compared to a "no tax" base case, applying tax revenue solely to deficit reduction initially lowers GNP about 0.4 percent below the base case. Over 10-15 years, however, GNP recovers and then exceeds the base case. GNP under a deficit neutral program (lower personal income taxes offset the gasoline tax) falls 0.4 percent under the base case and remains 0.3 percent below over the long term. A deficit neutral program (lower business payroll taxes offset the gasoline tax) follows base case GNP levels over time. These estimates are from macro-level models that do not account for ancillary benefits such as reduced congestion or air pollution.

[32] A debate is ongoing over the effectiveness of the CAFE standards. While improvement in new car fuel efficiency between 1975-1986 is not disputed, opponents to the standards point out that real gasoline prices tripled during that period. They argue that manufactures responded to consumer demand for high mileage vehicles in the face of rising fuel prices (and expectations of continued price increases). On the other hand, since gasoline only represents about 10 percent of total automobile operating costs, fuel efficiency may not significantly influence consumers' purchasing decisions—especially if consumers question characteristics such as comfort and safety of a more efficient car. A survey by J.D. Power and Associates found that fuel efficiency ranked last among 15 parameters consumers consider when purchasing new vehicles. Thus, without outside regulatory or financial incentives, motor vehicle fuel efficiency may not significantly improve. Krupnick et. al. estimated the cost effectiveness of increasing the CAFE standard to 37.5 miles per gallon at $106 per ton of carbon dioxide reduced.

Projections of the effect of a gasoline tax on vehicle miles traveled (VMT) requires the elasticity of demand for both gasoline and vehicle fuel efficiency (see sidebar). However, the economic literature reports a wide range for these elasticity estimates. In an unpublished study of the effect of a $1.00 increase in the gasoline tax, the Washington State Department of Transportation (WSDOT) identified a range of -0.5 to -0.8 for the long-run price elasticity of demand for gasoline and choose -0.7. They also estimated an elasticity for automobile fuel efficiency of 0.32 (relative to the price of gasoline).

The WSDOT study projects VMT in 2010 at 64.5 billion miles under current tax rates and 55 billion miles if the gasoline tax were $1.00 per gallon higher. This estimated 9.5 billion mile reduction in travel assumes people both drive less and purchase more fuel efficient vehicles when faced with higher gasoline tax. The huge reduction in travel and improvement in fuel efficiency would save 900 million gallons of gasoline and lower greenhouse gas emissions by 8.5 million tons. As Table 12 indicates, a gasoline tax would reduce emissions of other pollutants as well.

**TABLE 12**

**Effect of a Gasoline Tax on Pollution Emissions**

| Pollutant | Reduction (tons)† | Pollutant | Reduction (tons)† |
|---|---|---|---|
| Volatile Organic Compounds | 23,661 | Benzene | 1,656 |
| Carbon Monoxide | 192,969 | 1,3 Butadiene | 342 |
| Nitrogen Oxides | 21,978 | Formaldehyde | 195 |
| | | Acetaldehyde | 147 |

† Emission reduction estimates from the draft Ecology MSST report.

The revenue of a $1.00 tax per gallon of gasoline totals approximately $2.1 billion in 2010. Since these funds are available to lower other taxes or provide other services, they are not a "cost" but instead a "transfer" as defined by economists. The cost of the tax is found in the lost travel enjoyed by the public. Economic theory indicates a $124 million cost of reduced driving resulting from the tax in 2010. Thus, the overall carbon dioxide cost-effectiveness of a $1.00 gasoline tax is $14.60 per ton of emission reduced.[33]

**Feebates.** One alternative to CAFE standards is a FeeBate program which uses market forces to promote the acquisition of more fuel efficient vehicles. FeeBate systems set a standard efficiency against which motor vehicle efficiency is compared. A fee is charged purchasers of low fuel efficiency vehicles and a rebate is awarded to those who acquire high fuel efficiency vehicles. The actual fee or rebate depends on the amount the vehicles exceeds or falls short of a base mileage target. For example, assuming a base target of 30 mpg and a feebate of $100 per mpg, the purchaser of a vehicle achieving 35 mpg would receive a $500 rebate at the point of sale while a 23 mpg vehicle must pay a $700 fee. Generally, feebates are intended to be revenue neutral—to pay out the same amount in rebates as they charge in fees.

---

[33] The cost of a gasoline tax is the "dead-weight-loss" of driving less. The dead-weight-loss equation is

1/2*(change in miles driven)*(change in the cost per miles driven)

See Appendix B for this calculation. This estimate of a $124 million cost resulting from a $1.00 per gallon gasoline tax ignores other benefits of reduced driving such as lower congestion. An over simplified calculation of the congestion benefits assumes 500,000 hours of daily delay time in 2010 (an interpolation of delay times estimated by the Puget Sound Council of Governments' Vision 2020 document; 190,000 hours in 1990 and 830,000 hours in 2020). Assuming a 15 percent reduction in VMT reduces delay time by 15 percent, then 75,000 hours per day would no longer be wasted in traffic. Multiplying this figure by the average wage rate ($15/hour) and 250 working days reveals a congestion benefit of about $280 million. Eliminating almost 10 billion miles per year of vehicle traffic would also reduce the need for road construction and maintenance.

A recent Lawrence Berkeley Laboratory report estimated that a FeeBate of $100 per mpg differential could improve new car fuel mileage by 15 percent in 2010. Such an improvement in new vehicle fuel efficiency would lower annual carbon dioxide emissions by 4.4 million tons in 2010. However, the U.S. Department of Transportation (DOT) blocked an effort by Maryland to enact a FeeBate program. DOT held that fuel economy incentive programs are preempted by federal statute. Maryland's Attorney General, while conceding that certain aspects of the Maryland law violated the federal preemption otherwise affirmed the state's central right to enact a FeeBate. Presently, the legality of a fuel efficiency based FeeBate is uncertain.

## In-Use Motor Vehicle Fuel Efficiency

In addition to strategies encouraging people to acquire fuel-efficient vehicles, several programs can help improve in-use motor vehicle efficiency.

**Speed Limit Enforcement.** Vehicle fuel efficiency decreases as speeds rise; one rule of thumb is that vehicle fuel efficiency drops 1.5 to 2.0 percent for each mile per hour (mph) traveled above 55 mph. Approximately 35 percent of state vehicle traffic is on roadways posted at 55 mph or higher and almost 70 percent of this traffic travel faster than 55 mph.[34] Assuming these percentages remain the same in 2010, then enforcing the speed limit would save about 105 million gallons of gasoline and lower carbon dioxide emissions 662,800 tons. However, the cost of this program is on the order of $140 million due to increased travel time (excluding enforcement costs and safety benefits). A speed-limit enforcement program costs about $140 per ton of carbon dioxide controlled.

**Vehicle Inspection And Maintenance Programs.** Another way to improve fuel efficiency is to ensure that vehicles are properly operating. Motor vehicle inspection and maintenance (I&M) programs are designed to do just that.[35] Washington state currently operates a "normal" I&M inspection in most of King, Snohomish, Pierce, Clark, and Spokane Counties. Moving to an "enhanced" inspection program in these counties could save 24 million gallons of gasoline and lower carbon dioxide by 0.17 million tons in 2010.

Due to air quality problems in King, Pierce, Snohomish and Spokane Counties, enhanced inspections are federally required in those areas. Therefore, the ancillary carbon dioxide benefits are assumed to have no cost. Expanding the enhanced I&M program state wide adds $121 million to the program's cost and reduces emissions a further 340,000 tons, all at a cost effectiveness of $360 per ton. Exempting vehicles younger than 5 years lowers the additional cost to about $79 million per year, the carbon dioxide reduction to 0.26 million tons, and the cost effectiveness to $310 per ton. Expanding the program also reduces hydrocarbon, carbon monoxide, and nitrogen oxide emissions.

A slight modification of the I&M program could further improve efficiency. At any given time approximately half the motor vehicles have under inflated tires. These vehicles suffer efficiency loss of about one mile per gallon. Including a tire check/inflation during the I&M procedure would reduce gasoline consumption and carbon dioxide emissions about 3.7 million gallons and 35,000 tons, respectively. This measure saves more in reduced gasoline expenditures than it costs to conduct the test.

---

[34] Personal communication with WSDOT staff.

[35] EPA reports that the fuel efficiency of vehicles repaired after failing a normal I&M inspection improves about 5 percent while those failing an enhanced I&M inspection see a 12 percent boost.

**Remote Sensing.** A program similar to motor vehicle I&M is remote sensing. Remote sensing uses an infrared beam and combustion chemistry to measure exhaust emissions and vehicle efficiency. Remote sensing identifies vehicles in need of repair between regular I&M inspections. Vehicles identified by remote sensing as high-emitting are re-inspected and repaired as necessary. Remote sensing is a relatively inexpensive means to obtain virtually instantaneous measurements of on-road emissions and efficiency for large numbers of vehicles. However, remote sensing does have important limitations including:

- instantaneous vehicle exhaust concentrations can vary greatly;
- weather conditions limits its use. For example, the spray behind cars on wet pavement interferes with emission measurements. Ecology estimates weather would interfere with remote sensing about 10% of the time. Also, it cannot properly assess the emission characteristics of cold vehicles;
- it can only test across a single lane;
- alternating sites are needed to test a broad cross-section of vehicles;
- it requires reading of vehicle license plates. (To identify owners of vehicles with high emissions). Snow, road dirt, or trailer hitches may obscure license plate images. A 70 percent data 'capture' rate has been reported in remote sensing field studies.

The potential of remote sensing depends on how well it identifies out-of-tune vehicles and the extent to which it deters tampering with vehicle equipment. A combined remote sensing and enhanced I&M program could yield savings of 8.1 million gallons of gasoline in 2010 and lower carbon dioxide emissions by 77,000 tons. Combined with a normal vehicle I&M program, remote sensing could save 4.1 million gallons of gasoline and lower carbon dioxide emissions by 39,000 tons.[36] Sierra Research calculated the cost of such a program at approximately $500,000 per year assuming 20 weeks of on-road testing. This measure has a cost effectiveness of $770 to $490 per ton of carbon dioxide controlled.

## Alternative Motor Fuels

A third area of potential greenhouse gas reductions from the transportation sector is with the use of alternative fuels. Vehicles powered with some alternative fuels—compressed natural gas, ethanol, methanol—emit less carbon dioxide per unit of energy than gasoline. However, the greenhouse gas benefit of alternative fuels is not straight forward. A fair comparison includes the entire fuel production cycle, not just the emissions coming from the vehicle itself. As Table 13 illustrates, methanol from coal results in greater overall carbon dioxide emissions than gasoline while methanol from wood emits less.

An additional issue just now receiving attention is the effect of regulations established to deal with other environmental problems on carbon dioxide emissions. Fuel sulfur and aromatic content limits or minimum oxygen content require oil companies to more intensively refine petroleum which generally increases fuel cycle carbon dioxide emissions. The extent to which this regulation increases carbon dioxide emissions is uncertain. One estimate places world-wide regulation-caused carbon dioxide emissions at 1.4 to 2.7 million tons per day.

**TABLE 13**

**Alternative Fuels Full Cycle Carbon Dioxide Emissions†**

| Feedstock/Fuel | Fuel-cycle $CO_2$ equivalent emissions (grams/mile) | Change relative to gasoline (in percent) |
|---|---|---|
| Petroleum/Reformulated Gasoline | 469 | NA |
| Coal/ Methanol | 741 | 58 |

[36] Remote sensing also reduces other pollution. Ecology estimated that the program could reduce carbon monoxide emissions by 1,350 tons in 2001 in Spokane, assuming a 50 percent drop in vehicle tampering.

| | | |
|---|---|---|
| Coal/Compressed Hydrogen | 713 | 52 |
| Corn/Ethanol | 449 | -6 |
| Natural Gas/Methanol | 439 | -6 |
| Natural Gas/Compressed Hydrogen | 351 | -25 |
| Natural Gas/Compressed Natural Gas | 346 | -26 |
| Wood/Compressed Hydrogen | 117 | -75 |
| Solarelectric/Compressed Hydrogen | 84 | -82 |
| Wood/Methanol | 80 | -83 |
| Wood/Ethanol | -43 | -109 |

† OTA, Saving Energy in U.S. Transportation, 1994

**Vehicle Fleets Alternative Fuels Mandates.** The Energy Policy Act of 1992 establishes a schedule for state governments, natural gas and electric utilities, and propane distributors to acquire alternative fueled vehicles. Starting with the 1996 model year, 10 percent of vehicles purchased by these entities must use alternative fuels. By 1998, 50 percent of federal vehicle purchases are required to use alternative fuels. The Energy Policy Act allows DOE to apply a similar requirement to private and municipal fleets beginning in 1999. This analysis considers the effects of requiring half the vehicles in Washington fleets to operate on alternative fuels.

In 1990, Washington had 71 permanently registered fleets (e.g., Boeing) and 649 regular fleets. Assuming the permanent and regular fleets average 100 and 25 vehicles, respectively, then the fleets contained about 64,000 vehicles, or 1.5 percent of all state vehicles. If this percentage remains constant, then fleet vehicles will number about 105,000 in 2010, 52,500 of which must operate on alternative fuels (electric, natural gas, propane, and/or ethanol). Assuming these vehicles annually travel 20,000 miles per year (about double what the typical vehicle travels) and that an alternative gasoline vehicle achieves a fuel efficiency of 21.6 miles per gallon a fleet alternative fuel requirement would lower carbon dioxide emissions by 59,000 tons in 2010 (See Table 14.)

Based on bids for providing natural gas or propane vehicles for the state fleet, these vehicles are assumed to have a price premium of $3,000. Price premiums of $1,000 for ethanol fuel vehicles and $10,000 for electric vehicles are also assumed. (As the demand for alternative fuel vehicles increases, these cost premiums should fall.) Assuming the fleet vehicles roll-over every five years, the annual cost premium of an alternative fuels mandate for fleet vehicles is $105 million. This results in a cost-effectiveness of $1,800 per ton of carbon dioxide controlled.

**TABLE 14**

**Carbon Dioxide Reductions From a Fleet Alternative Fuels Requirement**

***Barriers to Electric Vehicles***

Technological advancement is needed for electric vehicles to compete directly with conventional cars. Storing electricity is the most daunting problem: batteries are heavy, expensive, short lived, limit vehicle range to under 100 miles and take several hours to recharge. Batteries under development should remedy some of these problems. An additional concern is cabin heating. Heating systems needed for cold season operation may negate much of the carbon dioxide emission reduction benefits. Public acceptance of operational limitations and maintenance requirements of electric vehicles is a final concern.

resources often have a significant greenhouse gas emissions advantage.

*Fuel processing*. Energy requirements for processing coal or biomass into usable fuels are much larger than the energy needed to produce gasoline. Similarly, natural gas and hydrogen incur large energy penalties for compression and liquefaction.

*Transportation*. Locally made fuels such as biomass-based methanol or domestic natural gas have less transportation cost than gasoline made with imported oil.

*Fuel Characteristics*. Fuel properties also affect vehicle efficiency: octane ratings affect compression ratios and thus efficiency; high flammability limits the use of lean burn engines, an energy saver. Energy density and phase (gas, liquid) also affects fuel efficiency due to storage requirements (volume and weight). Finally, alternative fuels have unique carbon contents, each produces various amounts of carbon dioxide per unit of energy combustion.

| Fuel | Carbon Dioxide Emissions Relative to Gasoline | Annual Reduction in Carbon Dioxide Emissions† |
|---|---|---|
| Electric | .50 | 57,200 |
| Natural Gas | .74 | 29,700 |
| Propane | .98 | 2,300 |
| Ethanol | 1.06 | -6,800 |
| | **Total** | **82,400** |

† 8.8 tons x (1-relative emissions) x 13,000 vehicles

**The California Low Emission Vehicle Program.** The California low emission vehicle program was created to reduce carbon monoxide, hydrocarbons and nitrogen oxides emissions. However, the zero-emission requirement for a certain proportion of new car sales does have the potential to reduce carbon dioxide emissions as well.

California's zero-emissions mandate is, in effect, an electric vehicle mandate.[37] Electric vehicles cause carbon dioxide emissions through their use of electricity. According to Table 15 the net carbon dioxide emissions from electric vehicles is slightly more than half the emissions of their gasoline fueled counterparts. Considering new vehicle penetration rates and assuming electric vehicles would travel the same distance as gasoline vehicles, then by 2010 approximately 4.5 percent of the State VMT would travel under electric power. This would lower carbon dioxide emissions by 0.49 million tons in 2010 (see Tables B-20 and B-21). However, due to technological limitations electric vehicles have a more limited traveling distance than gasoline vehicles. Therefore, 0.49 million tons may over-estimate the actual emissions benefit of the California low emission vehicle program.

Perhaps the most contentious issue surrounding the zero-emission vehicle mandate is the cost of electric vehicles. Cost estimates, ranging from $1,400 to $34,000 per vehicle, are difficult to compare because of differing assumptions about technological progress and the type of product consumers will accept. At this time, it is uncertain which estimate most closely reflects the actual costs that would result from adopting the California standards. This report assumes a $10,000 cost premium for electric vehicles. This cost translates into a cost effectiveness of $700 per ton of carbon dioxide reduction for the zero emission portion of California's low emission vehicle program (see Table B-22).

**TABLE 15**

**Lifetime Emission of Electric Vehicles Relative to Conventional Gasoline Vehicles†**

| Vehicle | | Energy Consumption | Lifetime Carbon Dioxide Emissions (tons) |
|---|---|---|---|
| Compact | GM Impact | (0.25 kWh/mile) | 11.1 |
| | Toyota MR2 | (28.5 mpg) | 33.3 |
| Mini-Van | Chrysler TEVan | (0.44 kWh/mile) | 19.5 |
| | Ford Aerostar | (23.4 mpg) | 40.6 |
| Full Size Van | GMC G-Van | (0.94 kWh/mile) | 41.6 |

[37] Under the Clean Air Act, states choosing to opt-into the California low vehicle emission program must adopt **all** of California's emission standards. Thus, vehicles sold in Washington would have to meet stringent hydrocarbon and nitrogen oxide emission limits as well as the zero-emission mandate. This analysis deals only with the effects of the zero-emission vehicle mandate; other parts of California's standards are not evaluated.

| | | |
|---|---|---|
| Dodge B250 Van | (17.7 mpg) | 53.7 |
| **Average Lifetime Emission Reduction, tons** | | **18.5** |
| **(percentage reduction)** | | **43%** |

[†]Assumes lifetime vehicle travel at 100,000 miles. Conventional vehicle data from EPA certification data. Carbon dioxide reduction estimates are highly sensitive to assumptions regarding the energy consumption of replaced conventional vehicles. For example, the average fuel efficiency of the conventional fueled vehicles in this table is 23.2 mpg. Substituting a fuel efficiency of 21.6 mpg (as projected by WSDOT for 2010), increases the carbon dioxide emission reduction to 0.58 million tons. Calculations for conventional vehicles do not account for deterioration in mileage or emission control components over time. See also Electric Vehicles, An Alternative Fuels Vehicle, Emissions, and Refueling Technology Assessment, WSEO, 1993.

## Modifying Demand

Altering transportation modes offers another potential way to achieve significant carbon dioxide reductions. However, the present transportation system is highly skewed against public transit. Our system evolved during a period of strong automobile subsides in the form of: low-cost or free parking, low density development patterns shaped by zoning, freedom from a variety of external costs (air pollution, noise, etc.), and government subsidized road construction. Decision makers must start from the current auto-orientated transportation infrastructure in devising strategies to increase public transportation ridership.

Most research on transportation mode choice emphasizes decisions commuters make between the automobile and travel by rail, bus, carpooling, vanpooling, or telecommuting. Efforts to understand and influence mode shifts have been motivated by desires to reduce traffic congestion and energy consumption, improve air quality, and plan infrastructure investments. Some options for influencing mode choice include:

- increase the cost of driving;
- control access to parking and highways, provide high occupancy vehicle (HOV) lanes;
- provide fiscal incentives to reduce costs to developer and business tenants who promote HOV use by their companies and employees, or that increase the cost of solo commuting relative to HOV modes;
- informational advertising and moral persuasion directed at businesses and individuals to promote or use HOV modes.

With the exception of a small (but growing) number of dedicated HOV lanes, these options have had little success in shifting commuting demand from private automobiles to HOV modes. People appear to highly value the privacy and convenience of the automobile. Local governments often find it difficult to impose the financial or regulatory burdens necessary to change people's travel behavior. In addition, these efforts are small compared to the substantial expenditures to support the automobile infrastructure.

**A Vehicle Mileage Tax.** Perhaps the most straightforward way to reduce travel demand is to raise travel costs. A vehicle mileage tax (VMT) tax directly accomplishes this goal. Motorists respond to increased travel costs by eliminating and consolidating trips, and by using alternative transportation modes. And reduced VMT translates into lower greenhouse gas emissions. Using WSDOT data, a $0.04 VMT tax is projected to lower vehicle travel by approximately 18.6 billion miles in the year 2010.[38] This huge reduction saves 866 million gallons of gasoline

[38] One difference between a VMT tax and a gasoline tax is the resulting compensating behavior. Individuals may respond to a gasoline tax by acquiring more fuel efficient vehicles. With a VMT tax the only compensating behavior is to reduce travel. Since the public has less flexibility under a VMT tax, a lower travel demand elasticity, -0.5, was presumed than for the gasoline tax analysis.

and lowers greenhouse gas emissions by 8.2 million tons. As Table 16 indicates, a VMT tax would significantly lower emissions of other pollutants as well.

**Driving Incentives**

According to Pickrell (1990) employer-provided free parking *"overwhelms any inducement for employees to commute by public transit that is currently offered by a partial tax exemption of the value of employer-supplied transit passes. At most, a free transit pass can be worth about $270 in annual taxable salary… [under] the 1984 Tax reform Act. In contrast employers' offers of free parking are typically equivalent to salary increases four times as large and can range in value up to ten or more times that amount."* *(emphasis in original)*

### Table 16
### Effect of a Vehicle Mileage Tax on Pollution Emissions

| Pollutant | Reduction (tons)† | Pollutant | Reduction (tons)† |
|---|---|---|---|
| Volatile organic compounds | 47,030 | Benzene | 3,222 |
| Carbon Monoxide | 383,520 | 1,3 Butadiene | 665 |
| Nitrogen Oxides | 43,680 | Formaldehyde | 378 |

† Emission reduction estimates from the draft Ecology MSST report.

Using the same methodology as for the gasoline tax section, the costs of a $0.04 VMT tax is calculated at $372 million. The overall cost-effectiveness of a VMT tax is estimated at $45 per ton of carbon dioxide removed.[39]

Administration of a VMT tax is likely to be quite difficult. Unlike a gasoline tax collected at the pump, a VMT tax requires periodic recording of odometer readings. Perhaps the easiest approach would be a VMT surcharge assessed at the time of vehicle registration. The difference in odometer readings between registration periods would determine the number of miles traveled. Likely concerns include establishing fee schedules for vehicles that travel out of state and vehicles that enter and exit the system. Administrative costs of a VMT tax were not included in the cost or cost-effectiveness estimates.

**Increased Parking Fees.** Parking is an integral part of motor vehicle operation. In fact, the cost of parking is often more than other vehicle operating costs (Pickrell 1991).[40] However, many commuters pay little to none of the parking costs. Employers often provide parking as an employee perquisite and cities often subsidize parking to generate benefits for the local economy. In addition, local zoning usually requires a minimum number of parking spaces per resident, employee or customer. The federal government exempts the value employees receive from employer provided parking from income taxes. Commuters who do not face the true costs of parking drive too much.

---

[39] Administration costs are not included in the cost estimate. The revenue raised by a $0.04 VMT would total approximately $1.8 billion. Similar to the gasoline tax, this cost calculation ignores benefits other than carbon dioxide reduction. For example, reducing VMT by 18.6 billion miles per year would have significant congestion benefits (estimated at $544 million using the same methodology as for the gasoline tax.) Similarly, reducing traffic would lessen the need for new road construction and for existing road repair.

[40] Assume that the average round-trip commute is 20 miles, gasoline costs $1.25 per gallon and vehicle mileage averages 20 miles per gallon. This translates into a daily vehicle operating cost of $1.25. This compares to parking costs in downtown Seattle that typically average over $5.00 per day (author's observation). For southern California Willson reports the per space fee range which recovers both the capital and operating costs at $71 to $143 per month ($3.40 to $6.90 per day).

Increasing the cost of employee parking is one way to force the commuter to realize more of the social cost of their driving decisions. And this should significantly affect commute travel demand.[41] Shoup and Willson (1990) developed a model which suggests that a $5.00 increase in commuter parking costs will reduce the number of vehicles arriving at a work site by 13 percent. Assuming that 20 percent of the State's VMT is commute related and that a $5.00 increase in parking costs affects 10 percent of commute trips, then VMT should go down by 168.2 million miles. This would annually save 7.8 million gallons of gasoline and lower carbon dioxide emissions by 74,000 tons.

A first-order estimate suggests the societal cost of a parking tax is low since it only involves a transfer of wealth; employees would begin paying for what employers currently offer for free. However, provision of free parking does work at cross purposes to other social objectives: reduced traffic congestion and air pollution. By advancing these other social objectives, increased parking fees may actually result in benefits in excess of its cost. On the other hand, it is clear the benefits will not be enjoyed equally. Commuters will bear the greatest portion of the costs while employers will reap much of the benefits. The overall cost-effectiveness of an increase in parking fees is estimated to be near $0 per ton of carbon dioxide removed.

Designing a parking tax or fee targeted towards commuters currently receiving free parking is difficult. Perhaps the most straight forward way to accomplish this is through the employers. For instance, the state could require employers to pay a parking fee for every employee not using a non-SOV mode of transportation. Alternately, parking operators could be required to provide information about employers who leased parking for their employees. If the employees were not charged for that parking, the employee could be subject to a tax. However, according to Ulberg, there is not known experience with either of these options.

**Trip Reduction Ordinance.** Trip reduction ordinances (TRO) are in place in several communities including Baltimore, Chicago, Houston, Los Angeles, New York, San Diego, and Milwaukee. Washington state's commute trip reduction (CTR) law requires employers in the counties of Clark, King, Kitsap, Pierce, Snohomish, Spokane, Thurston, or Yakima with 100 or more employees to reduce VMT and single-occupant vehicle (SOV) rates by 15 percent in 1995, 25 percent in 1997 and 35 percent in 1999. The current TRO applies to about 684 employers (Ecology). This evaluation considers the greenhouse gas mitigation potential of expanding the CTR to include employers with more than 50 employees; in the presently affected counties. The newly affected employers would reduce SOVs and VMT by 15 percent in the year 2000, 25 percent in 2002 and 35 percent in 2004.[42]

As a commute to work strategy, energy savings are calculated assuming 250 work days per year. Ecology estimates this strategy could reduce total annual VMT by about 72.5 million miles. This translates into a yearly carbon dioxide emission reduction of 23,000 tons. Using a model developed by Sierra Research, Ecology also calculated TRO costs. For the most part, Ecology input to the model cost data recommended by the Puget Sound Regional Council. (There is some discord regarding these cost estimates.) Expanding the program to include employers with

[41] Pickrell reports that after a Los Angeles government agency introduced market rates for employee parking, SOVs dropped from 42 to 8 percent and ridesharing increased from 17 to 58 percent. In Washington DC, parking charges at federal buildings imposed at half the market rate resulted in up to a 40 percent decrease in solo driving.

[42] Under Washington's commute trip reduction law (RCW 70.94.517) local jurisdictions must pass ordinances requiring large employers to develop worksite programs. Lowering the program threshold to 50 employees would require jurisdictions to update their ordinance and affect some jurisdictions for the first time.

over 50 employees is projected to annually cost $11 million. Thus the cost-effectiveness of this measure is $480 per ton of carbon dioxide eliminated.

**Rideshare.** A subset of TROs are ridesharing programs which encourage people to share rides during their commute trips. Existing rideshare programs in King, Snohomish, and Pierce counties have about 18,000 registrants. These programs provides no incentives to potential registrants beyond providing a list of potential participants. About 20 percent of registrants are placed into carpools. Kitsap county has a larger regional based program with explicit incentives for ridesharing. About 570 new car/vanpools have formed since Kitsap Transit's program began, with an average of 30 new registrants per week. The Kitsap Transit program shows the potential of a properly conceived and promoted community-based rideshare effort.

Expanding the current ridematching program in King, Snohomish, Pierce, and Kitsap counties to model the Kitsap Transit Smart Commuter Discount Program could further reduce VMT, gasoline consumption and carbon dioxide emissions. An expanded rideshare program would target work sites with 50 to 100 employees and large trip destination centers. In addition to a computer-generated match list, participants receive additional services such as 1) preferential parking, 2) guaranteed parking, 3) a Smart Commuter Discount Card entitling registrants to discounts at local businesses, and 4) a guaranteed ride home. Ecology estimates that such a ride share program could lower VMT by 43 million miles per year. This translates into carbon dioxide reductions of 13,600 tons per year.

Ecology estimated the costs of an expanded ride sharing program using the Sierra Research TCM model. For the most part, Ecology used cost data recommended by the Puget Sound Regional Council in the model. Assuming the costs calculated for the four Puget Sound counties are applicable outside those counties, a state-wide enhanced ridesharing program is estimated to cost $3.6 million. The cost effectiveness of this program is $260 per ton of carbon dioxide reduced.

**Telecommuting.** Businesses with telecommuting programs allow employees to work away from the primary worksite (usually at home). Telecommuting requirements vary from a desk at the remote location, to a telephone, or a computer with a fax modem. Software is currently available that allows home computers to communicate with office computers. Moreover, future technology will increase the type and number of tasks that individuals can complete away from the traditional workplace. Fiber optic cables, for example, should greatly increase computer data exchange and service capabilities.

Presently about 0.3 percent of the Puget Sound work force telecommute (Kunkle). Based on the Kunkle estimates, Ecology concluded that a ten-fold increase in telecommuting—3 percent of the work force, or 70,700 people—is feasible. According to Ecology, such a program would lower annual VMT by 43 million miles, gasoline consumption by 1.4 million gallons and carbon dioxide by 13,600 tons. To promote telecommuting, employers provide opportunities and/or incentives to employees to encourage working at home. Again using the Sierra Research TCM model, Ecology estimated the cost of a 3 percent telecommuting rate at $5.8 million. This estimate assigned a cost of $400 per telecommuter for set-up and $300 per employee for program administration cost.[43] The cost-effectiveness of telecommuting is estimated at $425 per ton of carbon dioxide reduction.

[43] The startup costs for telecommuting range from no cost to acquiring a phone line, purchasing a computer or acquiring other equipment. In the Puget Sound telecommuting demonstration project, 30 percent of participants

The benefits of telecommuting include reduced congestion. A DOE analysis found that telecommuting could reduce congestion delay in urban areas 3 to 5 percent (USDOE, 1993). Telecommuting participants may also receive ancillary benefits like: reduced exposure to air pollution; additional contact with children and reduced childcare costs; greater centralization of communities; and reduced commuting stress.

**Mass Transit System.** Mass transit systems are another way to reduce VMT. One mass transit system recently proposed for King, Pierce and Snohomish County area is projected to have a daily ridership of 560,500 when the system is complete in 2020 (Regional Transit Project, Environmental Impact Statement). Assuming full ridership annual VMT and carbon dioxide emissions would fall approximately 1 billion miles and 345,000 tons, respectively. However, huge and as yet uncertain quantities of fossil fuel will be needed to construct this system (construction of the system will take at least ten years).[44] Therefore, the aggregate effect on carbon dioxide emissions is uncertain. As such, the appropriateness of this measure as a greenhouse gas emission reduction strategy is not yet clear. On the other hand, other considerations such as congestion relief may make this project worthwhile. These other considerations are beyond the scope of this analysis.

**Transportation Multimodal Coordination.** Historically, transportation infrastructure, such as highways, transit, bike paths, and rail develop and operate independently. A lack of physical connections between modes creates user delays and requires multiple ticket purchases. Improved connections and compatible scheduling among buses, trains, ferries, van pools, shuttles, car pools, cars, bicycles, and pedestrians would make these systems more attractive to commuters. A further improvement would be a regional pass or single fare card good for use on all modes and across jurisdictions.[45] Creating the inter-connections necessary to allow users to move easily between systems will require a coordinated effort by the different operating agencies. An integral part of such an effort are public information and education programs.

Ecology estimates that transportation coordination can reduce VMT by 1.5 percent (bicycle improvements,

***Mass Transit in Washington***

An extensive mass transit system proposed for King, Snohomish and Pierce Counties was recently turned down by voters. The $10.3 billion system included 125 miles of electric-powered rapid rail running on an exclusive, grade-separated right-of-way and a 40-mile commuter rail line. In the north, service was proposed between downtown Seattle and Everett. The south Corridor ran from downtown Seattle to Tacoma. Eastside service to Seattle from Bellevue, Redmond and Issaquah was planned. A rail line linked Paine Field, Bothell, Kirkland, Bellevue, Renton and Burien. Commuter rail using existing freight and passenger railroad lines, also linked Seattle and Tacoma by way of the Green River Valley. Under the proposal, modified bus service would connect with the rail system as would HOV lanes and Park and Ride lots.

---

reported buying equipment at a median cost of $700. The overall average cost is thus $233 per telecommuter. I assume a $300 equipment cost per telecommuter plus $100 for "How to Telecommute" training, for a total of $400. The $300 program administration cost is between the public and private sector ongoing costs listed in Puget Sound Telecommuting Demonstration Executive Summary (WSEO). The Sierra Research model estimated costs for King, Kitsap, Pierce and Snohomish counties were inflated by 1.78 to project state wide costs.

[44] Massive amounts of energy are needed to construct a mass transit system. Healy and Dick, for example, analyzed the energy requirements of the BART transit system in California. They concluded that if the BART system were used for 50 years *"the [cumulative] energy required for propulsion will be roughly 40 percent of total energy. The other 60 percent is for construction (44 percent) and operation and maintenance (16 percent)."*

[45] With a regional fare card system all transportation agencies sell the card and accept its use. Its costs are between a simple pass system and a major electronic card reading system. Regional pass systems can have either a positive or a negative impact on transit ridership depending on pricing. We assume reasonable pricing and that participating agencies agree on appropriate revenue sharing.

0.5 percent; pedestrian improvements, 0.5 percent; a regional pass system, 0.3 percent; and transit schedule improvements, 0.2 percent)[46] or 1.3 million miles per year. This lowers carbon dioxide emissions by 410 tons. The cost of this program is estimated at $31 million per year for an overall cost effectiveness of $75,000 per ton of carbon dioxide control.[47]

Other benefits of improved intermodal connections include reduced trip and delay time, both for transit riders through better service and for vehicles through reduced congestion. Reducing the number of vehicle miles traveled should decrease costs for highway, street, and parking construction, maintenance, and repair.

**Land Use.** Land use and transportation planning are major influences on a community's structure. Transportation systems oriented to the car allow people to travel long distances to work, shop, and play. Land use patterns that physically separate residential, commercial and industrial areas, make automobile use a necessity. As an alternatively, transit-oriented development directs growth into existing urban regions. The increased residential and employment densities, and mixed-use commercial centers makes high capacity transit more attractive. Typically, transit-oriented development strategies take more than 20 years to implement. This strategy examines the changes in VMT brought about by introducing a transit-oriented development pattern into an existing urban region.

Transit oriented development creates pockets of high density work, and commercial and recreational mixed uses. These pockets overlay an existing urban region of low density single use areas with separated work, recreation and commercial activities. The goal of transit oriented development is to direct most new residential and all new commercial development to regional centers with the following characteristics.

- **Mixed Use Features**: High density residential, commercial and industrial facilities in close proximity to each other and within 1/8 to 1/2 mile of transit. A housing mix of small lot single family residences, townhomes, and apartments above first floor commercial development.
- **Residential & Employment Densities**: 7-50 dwelling units per acre within selected centers, with some center densities up to 70 units per acre. Between development centers, density below 5 units per acre. Employment densities of 60-75 employees per acre in the centers with significantly higher density in the major centers.
- **Transit Services**: Expanded bus, train and/or light rail service with good scheduling and route connections. Terminals for different modes (trains, buses, ferries) in close proximity to one another. All transit accessed with a single fare card. The transit service links employment, commercial, institutional and residential areas. 5-10 minute walking time to transit. 30 minutes or less transit travel times to employment areas.

---

[46] The data used to calculate the benefits of transportation coordination come from the Regional Transit Authority's 1992 Environmental Impact Statement. Estimates of the benefits of transit improvements vary widely. Apogee Research found a range of 0.03 percent VMT reduction for modest improvements in small communities to 2.57 percent for large investments, such as rail expansions, in large communities. Replogle concluded that bicycle and pedestrian improvements that enhance access to transit reduce VMT 0.5 percent in the short term and 2.1 percent in the long term.

[47] The final Environmental Impact Statement for Vision 2020 estimated $200-$300 million for pedestrian and bicycle facilities improvements. Ecology estimated the other costs below:

| INTERMODAL IMPROVEMENTS | COST (millions) |
|---|---|
| Arterial related bicycle & pedestrian | $81.8 |
| Bicycle & pedestrian | $300.0 |
| Route scheduling | $0.2 |
| Regional Pass | $1.7 |
| TOTAL COST | $382.7 |
| ANNUAL COST (20 years, 5%, amortized) | $30.7 |

- **Pedestrian Features**: Pedestrian routes are both shared (sidewalks adjacent to access streets) and separate facilities. Within the centers, commercial and industrial activities between transit facilities and the residential areas; walking times and distances to these facilities are equal to or less than those for transit service.
- **Bicycle Features**: Bicycles routes are both shared and separate facilities. On local access streets bicycles share the road with vehicles. On higher capacity streets bicycles have reserved lanes and separate paths within the right-of-way.

Quantifying the effectiveness of land use mixing and densification in reducing VMT is difficult. Ecology compared continuation of existing community plans (i.e., transit share of commute trips of 10 percent) transit oriented development (i.e., transit share of commute trips increases to 15 percent) Ecology concluded that over the long run transit oriented development would lower VMT by 2.7 percent.[48] Based on this estimate, annual gasoline consumption falls by 71,000 gallons in the Puget Sound region (transit orientated development is an urban area program). This would result in 670 fewer tons of carbon dioxide emitted into the atmosphere.

The cost difference between high density planned development such as this strategy and a lower density sprawl strategy can vary depending on the assumptions, and how a community charges for its facilities and services.[49] Ecology assumed that the money spent on transportation remains the same, but is spent differently, e.g., less road building and more transit. Therefore, the only costs considered are those to develop and update urban area comprehensive plans, estimated at $5 million.[50] Assuming these plans have a ten year life, the annual cost of this program is $680,000. The cost-effectiveness of this program is $1,000 per ton of carbon dioxide control. One difficulty with this strategy may be how and whether to compensate property owners in designated rural areas for taking the development rights from their land.

## Trains

**Electric Trains.** Trains consume significant quantities of energy in Washington state. Nationally, diesel trains consume 10 percent of all distillate fuel (Edison Electric Institute). Assuming this is also the proportion in Washington and that this trend continues, then diesel trains will consume approximately 75 million gallons of distillate fuel and emit 839,000 tons of carbon dioxide in 2010. Since electric trains enjoy a 15 percent advantage over diesel trains in terms of carbon dioxide emissions (Edison Electric Institute), electrifying Washington trains would annually lower carbon dioxide emissions by about 200,000 tons.

The cost of electrifying trains in Washington is not known. Stringing overhead power lines will cost a substantial sum. Another problems is that electricity over long distance routes must come from several utilities. Nevertheless, several studies indicate that relative to automobiles and

[48] The literature contains varied estimates of how much VMT growth can be reduced. A 2.7% reduction is at the low end and 10% at the high end of estimates. In Washington a significant amount of existing housing, commercial, and industrial sites are already located outside the transit oriented development centers. Consequently, the VMT reduction expected for Washington is assumed at the low end of the estimates.

[49] Many variables can affect the cost of different development strategies. Density, lot size, road widths, household size, location of development, distance to central public facilities, size of the urban area and how aggressively the community pursues higher densities and limits new road construction all affect development costs. Generally, high density development is cheaper than low density sprawl. In addition, land use strategies address more concerns than air quality, including congestion, energy conservation and the quality of life.

[50] Currently, communities which are subject to the Growth Management Act have spent an estimated $100 million dollars updating their plans. Seattle has spent about $5.5 million (about $10/resident), Vancouver $1.5 million and Yakima $1.1 million (about $25/person) on development of comprehensive plans to date (Carlson).

trucks, electric rail service is an efficient and low cost means of transporting goods and people (when subsidies to and externalities associated with public roadways are included).

**Truck To Train Mode Shifts.** Many estimates have been made about the efficiency of various modes of commodity transportation services. The OTA (1994) reports that for 1990, *"the average energy intensity for inter-city freight movement by truck was 3,357 Btu per ton mile, whereas the average intensity for train transport was 411 Btu per ton-mile, a ratio of 8:1. However, an examination of the energy consumption by both trucks and trains for moving identical cargo over the same routs, suggests that trucks use 1.3 to 5.1 times as much energy as trains do."* An Oak Ridge National Laboratory estimate assumes trains consume about 12 percent of the energy per ton mile as trucks. Presuming a conservative in-use energy consumption truck-to-train ratio of 3:1, then approximately 330 pounds of carbon dioxide emissions is reduced for every 1000 ton-miles of freight diverted from trucks to trains.

The second key unknown in estimating the energy savings potential of mode shifts is the amount of freight that could be shifted. OTA reports that trucks move about half of the non-bulk, long-haul freight traffic. Shifting all the competitive freight would double present-day long-haul non-bulk train movements. This would raise annual train carbon dioxide emission about 840,000 tons and lower truck emissions by 2.52 million tons for an overall emission reduction benefit of 1.68 million tons. The feasibility of such a shift depends on both the proximity of current rail facilities to cargo origination and destination points and the capacity of rail facilities to absorb new load. While the second part of this equation is likely met (the national rail network operates at about 20-25 percent of capacity), whether rail facilities are located to take advantage of a shift is uncertain.

Possibly the most direct government policies to promote rail transportation are subsidies or tax breaks. At present the amount of mode shifting achieved by any particular financial incentive is not known. Therefore, I could not calculate a cost effectiveness estimate of this carbon dioxide emission reduction strategy.

**WSDOT Grain Train.** WSDOT recently initiated an interesting program to improve the long-term viability of short-line rail roads in Eastern Washington. Rail carriers typically assign covered hopper grain cars to long-haul markets because they yield high profits. As a result, Washington wheat shippers (short-haul rail customers) must truck grain to river ports for barge transportation. WSDOT reports that 800 to 1000 rail carloads of grain are lost to trucking annually due to car shortages. In response, WSDOT purchased 29 hopper cars to supplement the grain transportation capacity of railroads in Washington.

According to WSDOT, the rail cars cost $730,000 to purchase and repair. However, the grain train has benefits far in excess of this cost: $300,000 by shippers (annually) due to lower transportation costs; $500,000 by state and local jurisdictions (annually) through reduced road repair costs; regional benefits from a more competitive multi-modal transportation system; and environment benefits from reduced consumption of fossil fuels.[51] WSDOT estimates that the grain train saves over 10,000 gallons of diesel fuel and lowers carbon dioxide emissions by 110 ton per year. Moreover, expanding this program to 68 cars could save an additional 35,000

[51] A second energy benefit not counted here is from reduced barge traffic on the Columbia river. A "back of the envelope" calculation suggests that the water used to operate the locks at Bonneville dam a single time would produce about 1750 kWh of electricity if run through the dam's turbines. To the extent that the grain train reduced barge traffic, it also increases the water available to produce electricity.

gallons of fuel and reduce emissions by over 500 tons per year. Finally, This program has the great advantage of saving much more money than it costs even without consideration of the greenhouse gas reduction.

## Airplanes

**High-Efficiency Commercial Airplane Engines.** Commercial jet fuel is one of the fastest growing areas of fossil fuel consumption. Between 1990 and 2010 consumption is projected to almost double and carbon dioxide emissions are estimated at over 19 million tons. One way to reduce these emissions is to improve aircraft fuel efficiency. The Ultrahigh bypass high-efficiency, unducted fan engine was developed specifically for this purpose. General Electric designed, demonstrated and certified this engine during a time of high fuel costs (and high expected fuel costs). Drawbacks of this engine are a high purchase price ($1 million over a traditional engine) and its limitation to rear-engine configured airplanes. ICF estimates that this engine could reduce overall jet fuel consumption by 4.0 percent in 2010.[52] Assuming the ICF estimates are correct, widespread adoption of this engine could reduce greenhouse gas emissions about 800,000 tons in 2010. The cost effectiveness of this engine in terms of carbon dioxide reduction is positive—it saves more money than it costs.[53] However, given the mobile nature of airplanes and interstate commerce concerns the state could do little to promote acquisition and use of these engines. Progress in these areas depends upon federal action.

[52] A 4.0 percent reduction in fuel consumption may be high for Washington State. Much of this State's projected growth in air travel involves international pacific rim flights. Airplanes servicing these routes typically have an underwing engine configuration which precludes use of the unducted fan engine.

[53] Assuming a cost premium for the engine of $1 million, average annual fuel savings of 200,000 gallons for 15 years and fuel costs of $0.60 per gallon (also assuming that the price inflation for jet fuel approximately equals the general rate of inflation). All estimates from ICF.

## The Electricity Generation Sector

A final area of significant potential to reduce greenhouse gas emissions is in the generation of electricity. Presently this sector emits a relatively small amount of greenhouse gases relative to the national average due to state reliance on hydroelectric generation (and some nuclear power). However, current environmental restrictions along with a lack of suitable future dam sites limits additional development of hydroelectric resources. New generating resources are expected to be primarily natural gas fired combustion turbines. Between 1990 and 2010 natural gas use by utilities is expected to increase 854 fold. By the year 2010 carbon dioxide emissions from these plants are projected at 9.77 million tons. This section looks at the potential to substitute some of this increase with renewable generating resources: specifically wind, solar and biomass.[54]

**Wind Power.** Contemporary wind projects are typically rated at 25 to 100 MW. A 25 MW project might have 60 to 70 turbines covering 1500 acres. Turbines, while reminiscent of aircraft propellers, are specifically designed for electrical generation. The blade and generator housing, or nacelle, pivots to face directly into the wind. Each turbine is rated at about 300 to 500 kW of capacity. Turbines are usually arranged in rows oriented at right angles to the direction of the prevailing winds and spaced at two to five rotor diameters from each other. Rows of turbines are usually located with roughly 10 rotor diameters between them. Wind projects typically produce power about 95 percent of the time at an average output of 28 - 35 percent of rated capacity.[55]

The potential for wind energy in Washington State is practically limited by the windiness of an area, competing land uses and the cost of project development. The minimum average wind speed suitable for commercialization is 16 mph. The 1991 Northwest Power Plan estimated the State's wind resources at 450 MW. However, technology improvements have expanded the wind resource potential. Current wind turbines would produce about 900 MW at these same sites (Lynette). Moreover, recent wind monitoring revealed a 400 MW site on the Washington/Oregon border which was

***Wind Projects in Washington***

Currently no wind energy projects operate in Washington. However, several are planned. The Conservation and Renewable Energy System (or CARES), a joint operating agency with eight Public Utility Districts, has begun a 25 MW project in Klickitat County. Two private utility companies, Pacific Corp. and Portland General Electric, have begun the process to permit a 100 MW wind project also in Klickitat County. And, Kenetech has bid a 100 MW capacity wind project for the Snohomish County PUD near Walla Walla in eastern Washington.

In addition, Washington companies manufacture wind generation equipment. Heath Techna makes wind blades in Kent, principally for the California market. AWT may build turbines in Port Angeles. Ninety of these turbines would be used in the CARES project. These companies are well situated to compete in the expanding world market for wind generated electricity—India, for example, intends to obtain 900 MW of wind generation—and are helping Washington maintain a leadership role in high technology.

---

[54] As an alternative to renewable energy resources, some have suggested direct removal of carbon dioxide from combustion turine flue gases. However, the thermal efficiency penalty makes such efforts impractical. Another proposal by Hihous et. al. is to reform the fuel prior to combustion to remove the carbon dioxide. This process would mix methane with superheated steam to form hydrogen and carbon dioxide.

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

The carbon dioxide is then separated and disposed of deep in the ocean. The remaining hydrogen is combusted producing only water vapor. The uncertainties of this approach include its cost, its thermal efficiency and the ecological effects of ocean carbon dioxide disposal. At the moment, this and other carbon dioxide "scrubbing" alternatives are only conceptual in nature and therefore, will not be discussed further.

[55] Much of the information about wind electricity generation for this section came from Mike Nelson of the Washington State Energy Office.

not included in the current resource assessments. The Battelle Wind Energy Resource Atlas of the U.S. estimates that approximately 2 million acres of Washington's land has class 3 or better wind speeds. (A class 3 wind has an average speed of above 14.3 mph.) If half this area is suitable for wind development then the potential wind resource is about 2000 average megawatts.[56]

Wind energy has several attractive attributes. First, wind turbines are small and modular. By producing modular units in quantity, economies of scale help to reduce costs. Second, a wind farm's generation potential can be sized according to current electrical demand. This reduces commitment of capital in unused generation capacity and lowers investment risks. Third, wind energy consumes no fuel and therefore is not vulnerable to future rises in fuel prices. Finally, although wind farms occupy many acres, that land remains available for its traditional use such as pasture or agricultural production as little of the site is permanently occupied.

The principal drawbacks of wind energy have been its cost and the intermittent nature of wind. The cost concern has largely dissipated. In the 1980s cost of wind resources averaged around \$0.50 per kWh. However, according to the Electric Power Research Institute wind costs are now *"…about the same as power from more conventional sources."* While requiring high initial investment, the lack of fuel costs make wind power competitive with many traditional energy sources. For example, Zond Systems, Inc. recently won a bid in Minnesota to provide wind energy at a cost of \$0.030/kWh. (This bid includes the federal Tax credit, without which the cost would be \$0.036/kWh).

The intermittent nature of wind gives rise to concerns about its ability to supply base-load needs. However, it elegantly compliments the regional hydroelectric energy system. The electricity generation capacity of hydro system is limited by the amount of water behind the dams. Wind generation can supplant hydro generated electricity and thereby save water for power generation or fisheries management. Furthermore, the peak production of some wind sites occurs during the winter which may help meet peak demand.

As discussed above, the cost of wind generated electricity is approximately the same as for natural gas combustion turbines. Therefore, the cost of supplanting combustion turbines with wind generation is essentially zero. This results in a cost-effectiveness of carbon dioxide reduction of \$0 per ton. The annual carbon dioxide reduction that would result from adding 500 MW of wind resources (nameplate capacity) totals approximately 450,000 tons. The cost of constructing 500 MW of wind resources would total about \$500 million.

Not withstanding the comparable life-cycle costs, the traditional regulatory cost-recovery structure for energy projects impedes the development of wind power. Under the current structure the fuel costs of fossil fuel generation—a significant portion of total costs—are spread over the life cycle of the project. The structure front loads the higher capitol costs of wind power making electricity rates higher than a comparable fossil fuel generation facility during the early years of the project. It is ironic that wind's lack of fuel costs, while clearly a positive attribute, puts it at a disadvantageous position relative to fossil fuel projects. Washington could assist in lowering this barrier to wind energy development by allowing capitol cost recovery over the entire life of the project, and assisting with low interest project financing and tax incentives

[56] The Battelle Wind Energy Resource Atlas of the U.S. estimates wind resources in Washington at nearly 3,750 average megawatts. However, it is unrealistic to assume development in all land with wind generation potential.. According to WSEO staff a more plausible maximum wind potential estimate is around 2000 MW.

targeted to renewable projects. spreading state sales taxes on wind over the life cycle of the project.

**Solar Photovoltaic Systems.** Distributed photovoltaic systems usually consist of fixed rooftop arrays and a DC to AC inverter installed at the electrical panel. The arrays typically have a 4.0 kW nominal capacity though electricity generation depends on the energy level of sun light (averaging 4.8 kWh/$m^2$/day in Yakima and 3.8 kWh/$m^2$/day in Olympia). An estimate by WSEO places the State's potential for solar electricity generation at about 4000 MW. Benefits of photovoltaic electricity to utilities include delaying substation replacement, extending equipment maintenance intervals, reducing electric line losses, and improving distribution system reliability.[57]

The main impediment to widespread photovoltaics use is its cost. The current cost of electricity generated with photovoltaics is around $0.13 - 0.15/kWh more than natural gas turbines—it is expensive electricity.[58] However, costs are falling. A 4.0 kW panel cost $14/Watt in 1992, today it costs about $4/Watt. Maycock predicts prices at $2.00 - $2.50/Watt by 2000. A stable market for photovoltaic equipment is essential to continue the fall in prices.

The $0.14 /kWh cost differential in electricity generation results in a <u>carbon dioxide reduction cost-effectiveness of $220 per ton</u>. A state wide program to place photovoltaic arrays on 10,000 residences (half in eastern Washington and half in western Washington) would annually generate approximately 9.3 MW (81,374 MWh) of electricity, reduce 59,800 tons of carbon dioxide emissions and cost approximately $46 million. Assuming economics of scale lowers the cost differential to 11 cents/kWh, the cost per ton of carbon dioxide reduction is $150.

The state could improve prospects for solar generated electricity and reduce its costs through long-term pilot programs, demonstration projects, and research and development grants.

**Nuclear Powered Electricity Generation.** Nuclear power, though it posses other environmental concerns, is one viable

***Photovoltaics in Action***

The SMUD photovoltaic program employs volunteers (PV Pioneers) who allow the utility to install 4 kW systems on their roofs. The system consists of photovoltaic modules, an inverter and wiring and is directly connected to the grid. SMUD views rooftop applications as free land with no EIS, no development hassles and no transmission line extensions. There is no dual metering, all electricity flows to the grid. The customer is charged a "green rate" premium of 15 percent per month of the individuals bill.

A SMUD phone survey found over 2000 willing "PV Pioneer" customers — 26 percent of the general population and 57 percent of the "green" population. SMUD installed 108 residential systems and one commercial system in 1993 and planned to install 134 residential and 8 commercial rooftop systems in 1994. This totals of 613 kWh rooftop photovoltaics. Because of the great response SMUD expects to install 100 photovoltaic systems per year over the next 5 years.

Current trends in the utility industry would reduce the prospects for photovoltaics. Should retail wheeling remove utilities from the central role of purchasing electricity, it may also eliminate the funding source of demonstration projects which give rise to stable demand. Retail wheeling may also affect solar power by focusing competition only on price; neglecting other concerns about traditional generation resources.

---

[57] Much of the information about photovoltaic generation systems in this report came from Mike McSorley of the Washington State Energy Office.

[58] 1994 Component costs estimated by the Sacramento Municipal Utility District (SMUD) were: $6.48/watt including installation, inverters and mounting system (arrays $4.00/watt; inverters $1.00/watt, installation $1.00/watt, mounting $0.28/watt, miscellaneous $0.20/watt): $0.90/watt for utility administration, (includes interconnections, metering, site preparation, district labor, administration, overhead, tax, bonding, and O&M). . Total cost of system was $7.38/watt. Replacement costs of $2.76/watt were estimated for the year 2000. Finally decommissioning costs including removal of the system would approximate the installation costs plus roof hole repairs, through-the-wall hole repairs and powerline disconnect.

option to reduce carbon dioxide emissions. Indeed, France relies heavily on nuclear power as a source of electricity and has *per capita* greenhouse gas emissions about one-third of U.S. levels.

There is one nuclear powered electricity generation facility operating in Washington, WNP-2. Its nameplate capacity is 1173 megawatts of electricity, though it typically generates around 1160 megawatts when operating. Frequent shutdowns have reduced plant performance. For example, in 1994 WNP-2 had an operating capacity factor of 71.8 percent and generated about 840 average megawatts of electricity (Washington Public Power Supply System). WNP-2's 1995 capacity factor goal is 78 percent. As a non-fossil fuel source of electricity, the 840 megawatts generated by WNP-2 displaced approximately 2.96 million tons of carbon dioxide emissions relative to a combustion turbine.

Given the environmental concerns surrounding nuclear power and the perceived high cost some argue for shutting down the plant. While this report takes no position on those environmental issues, it clearly emits less carbon dioxide than fossil fuel generating facilities. Table 17 presents the cost per ton of carbon dioxide control of nuclear power relative to its cost premium. For example, if nuclear power costs three mills per kWh more than electricity produced with a combustion turbine, the carbon dioxide control cost effectiveness is $7.50 per ton.[59]

**TABLE 17**

**Cost Effectiveness of Nuclear Power as a Carbon Dioxide Reduction Strategy†**

| Cost Premium (Mills/kWh) | Carbon Dioxide Reduction Cost Effectiveness (Dollars/ton) |
|---|---|
| 1 | 2.50 |
| 2 | 5.00 |
| 3 | 7.50 |
| 4 | 10.00 |
| 5 | 12.50 |
| 6 | 15.00 |
| 7 | 17.50 |
| 8 | 20.00 |
| 9 | 22.50 |
| 10 | 25.00 |

† Assumes the displaced electricity source is a 50 percent efficient combustion turbine.

**Biomass Fueled Electricity Generation.** Biomass fuels offer a unique energy resource for electric generation. Biomass fuels include any organic matter available on a renewable basis (e.g., agricultural and woody crops grown for fuels forest residues, wood product residues, agricultural field residues and processing wastes, animal wastes, and municipal solid waste). They generally are a co-product from our needs for food, fiber, and structural materials. Most are considered waste products and are available for the cost of transportation. However, their low energy densities, relative to coal or petroleum, limits the distance they can be economically transported. About 1,000 trillion British thermal units (TBtu) of biomass residues are generated each year in the Pacific Northwest.[60]

[59] From an economic standpoint this measure of cost effectiveness is incorrect. This is because the cost premium includes repayment of money spent to build the plant. The economically proper way to calculate cost effectiveness is to ignore such "sunk" construction costs and only consider the marginal cost of plant operation. Excluding sunk costs would significantly reduce electricity costs of the already constructed WNP-2.

[60] Unless otherwise noted, the information about biomass fuels in this report came from a draft Washington State Energy Office report to the Northwest Power Planning Council by Jim Kerstetter.

> ***Current Biomass Use in Washington***
>
> Washington lost about 30 MW of biomass generating capacity with the closure of the Skagit County Resource Recovery Project, the North Powder, Blue Mountain, and the Pine Products products. Changing economic conditions drove the closures.
>
> Additions to biomass power include the Tacoma Steam Plant retrofit which came on-line in 1991. This 50 MW facility co-fires coal, biomass and refuse derived fuels. Scott Paper and the Snohomish County Public Utility District are partners in a 52 MW cogeneration facility using hog fuel and spent pulping liquor.

Today, approximately 1,000 biomass-fueled electric generating facilities operate in the United States, one-third of which supply power to the grid. Some biomass fuels, such as woody residues have a long history of use for generation. For others, like municipal solid waste (MSW), interest has risen and receded with promulgation of environmental regulations and alternative uses of the materials. DOE has an ambitious plan to provide as much as 50,000 MW of biomass power by the year 2010. The program includes improving the performance of today's biomass power plants, evaluating and utilizing biomass fuels for co-firing, developing next-generation technologies, and assuring availability of biomass fuel supplies from dedicated feedstock supply systems.

Systems to generate electricity from biomass materials vary depending upon the input fuel (see Table 18). At least three mature technologies are fueled by woody materials, forest and mill residues: stoker power plants, wood gasification/combined cycle power plants and fluid bed combustion. These systems are also suitable for burning agricultural field residues fuel. Landfill gas systems use either internal combustion engines or gas turbines to produce electricity. Anaerobic digester systems are used to process animal manure.

**TABLE 18**

**Fuels, Technology, and Sizes**

| Fuel | Technology | Unit Size (MW) |
|---|---|---|
| Wood/Agricultural Residues | Steam | 10,25,50 |
| Wood/Agricultural Residues | Circulating Fluid Bed | 10,25,50 |
| Wood/Agricultural Residues | Wood Gasifier/Combined Cycle | 10,25,50,100 |
| Landfill Gas | IC Engine | 5 |
| Animal Manure | IC Engine | 0.5 |
| Chemical Recovery | Steam | 20 |

Biomass fuels offer important greenhouse gas reduction benefits even though, on an energy basis, their carbon dioxide emissions are comparable to coal. As biomass biodegrades, it releases carbon dioxide and methane to the atmosphere. Therefore, combusting biomass to produce electricity only accelerates the release of biomass carbon into the atmosphere <u>and</u> offsets the carbon dioxide emissions from traditional fossil fuel sources. For this reason, this report assumes the net contribution of combusting biomass to global warming potential is zero.

<u>Woody Residues</u> encompass two potential biomass fuels, forest residues and mill residues. Forest residues include material left after a timber harvest, stagnant and dying timber, hardwood stand conversions, and pre-commercial thinnings. Data on forest residue availability and cost is limited. However, interest is growing in recovering materials from forests to protect health and reduce fire danger.[61] A report prepared for the Pacific Northwest and Alaska Bioenergy Program estimated that at a value of $0.30 per cubic foot (including chipping and hauling), 4,350 MBtu of

[61] Recovery of logging residues solely for energy production is economically tenuous. However, residue recovery often is designed to achieve multiple objectives such as slash removal requirements or stand improvements. Such other objectives help to lower the cost of using logging residues for energy production.

woody residuals would have been extracted from Washington forests in 1990.[62] Scaling this estimate by the expected reduction in timber harvest suggests 2,350 MBtu of forest residues economically available for energy production in 2010 (assuming no change in extraction costs or value of woody residuals).

Mill residues are generated when timber is converted into lumber and plywood. The quantity of residue per board foot of lumber produced and per square foot of plywood available for power generation has dramatically fallen over time. Kerstetter estimates that region-wide mill residuals will total only 7,000 MBtu in 2009. Scaling this estimate by 0.45 to account for Washington's portion of regional timber production results in a projection of 3,150 MBtu of mill residuals available for energy production in this state. Altogether, 5,500 MBtu of woody residuals are assumed to be economically available to produce electricity in 2010.

Characteristics of alternative wood-fired power plants are described in Table 19. These boilers produced about 7.9 aMW per trillion Btu/year of forest residues and mill residues burned. Thus, this energy source could supply approximately 43.5 aMW of electricity in 2010. If this energy production displaced a high-efficiency combined-cycle natural gas fired combustion turbine, then carbon dioxide emissions would fall by about 150,000 tons. (Assuming the woody residue would release carbon dioxide anyway through the biodegration process or by being burned.) The cost of this reduction is about $80 per ton of carbon dioxide eliminated.

**TABLE 19**

**Performance and Economics of Wood-Fired Power Plants†**

| Combustor Technology | 25 MW Plant | 50 MW Plant |
|---|---|---|
| **Stoker Power Plant** | | |
| Net heat rate, Btu/kWh | 14,393 | 14,380 |
| Fixed, $/kW - yr. | 99.1 | 68.3 |
| Total Cost/kWh (cents) | 8.3 | 6.7 |
| **Fluid Bed Combustor** | | |
| Net heat rate, Btu/kWh | 14,356 | 14,342 |
| Fixed, $/kW - yr. | 108.3 | 75.5 |
| Total Cost/kWh (cents) | 9.3 | 7.5 |
| **Wood Gasification/Combined Cycle Power Plant** | | |
| Net heat rate, Btu/kWh | 12,818 | 12,818 |
| Fixed, $/kW - yr. | 181.3 | 124.6 |
| Total Cost/kWh (cents) | 12.4 | 9.6 |

† Based on Kerstetter (1995) estimates.

Chemical Recovery Boilers recycle the chemicals used to pulp wood into fiber. They also reduce wastewater discharges and produce steam. Of Washington's 19 mills, 9 have chemical recovery boilers. Four of these boilers produce 87 aMW of electric power. WSEO estimates that upgrades to those four boilers along with new generating equipment at five other boilers would increase the electricity generating capacity in this sector to over 203 aMW. Indeed, the Scott Paper Company in Everett is in the process of installing new hog fuel boilers and running excess steam through a 52 MW turbine generator to produce electricity. The cost of the Scott Paper Company project is estimated at $600/kW (Kerstetter). While costs vary significantly among the different sites, a $600/kW seems a reasonable estimate, and therefore serves as the basis for estimating the cost of adding electric generation to the other chemical recovery boilers.

[62] A $0.30 per cubic foot value of woody residuals is approximately equal to a hog fuel cost of $25 per ton. Current hog fuel prices average around $20 per ton but can vary up to $30 per ton.

The 116 aMW of electricity estimated as available from this sector is based on current firing rates, steam requirements and chemical streams. Therefore, the sole cost of this electricity is the capitol costs to upgrade the boiler and add electricity generation equipment. Assuming a 90 percent capacity factor and spreading capital costs over twenty years results in a $0.006 cost per kWh. Compared to natural high-efficiency gas fired combustion turbines, the electricity generation from chemical recovery boilers lowers carbon dioxide emissions by about 410,000 tons. No cost-effectiveness estimates were made for this measure since it costs less to produce power from this source than from natural gas fired combustion turbines.

Agricultural Field Residues are a byproduct of producing grain. While highly variable, about 50,000 million Btu of residues are annually left on Washington fields (3,000 pounds of residue per acre). However, the residues available for generating electricity depend upon the agronomic requirements for soil fertility and erosion control. The technology to combust agricultural residue is similar to that for wood residues. Therefore, the capital cost of $0.050 per kWh is assumed, based on a 50 MW stoker power plant. To procure agricultural residue fuel, one must collect, transport, store the residue and add fertilizer to fields to replace nutrients otherwise provided by the residues. Cost estimates of these activities are provided in Table 20.

Based on these estimates, the overall cost of using agricultural residues to produce electricity was calculated at $0.082 per kWh (including the cost of a 50 MW stoker type plant). State Carbon dioxide emissions would fall by 282,000 tons for each plant at a cost effectiveness of $93 per ton of reduction. Agricultural field residues are not currently used in Washington to produce power but are used in some other areas notably California.

**TABLE 20**

**Costs of Procuring Agricultural Field Residues**

| Cost Component | $/ton | $/MBtu |
|---|---|---|
| Collection | 11 | 0.73 |
| Fertilizer | 3 | 0.20 |
| Local Storage | 4 | 0.27 |
| Transportation | 10 | 0.66 |
| **Total** | **32** | **$2.20** |

Municipal Solid Waste is another potential energy fuel. However, its potential to reduce greenhouse gas emissions depends on alternative disposal options. Generally speaking, contemporary land fills are designed to prevent water infiltration as much as possible to protect ground water from contamination. Without water, land fill materials do not biodegrade. Therefore, neither carbon dioxide (a result of aerobic digestion) or methane (a result of anaerobic digestion) are emitted in great quantities from new land fills. With regard to older land fills, the situation is quite different. Constructed at a time of less stringent environmental regulations, these landfills are considerably wetter than newer ones. However, by the year 2010 most older landfills are likely to be closed. Therefore, combusting MSW to produce electricity should not significantly affect greenhouse gas emissions to the atmosphere.

Landfill Gas is produced as a result of decomposition of organic matter in landfills. The gas is composed of approximately 50 percent carbon dioxide and 50 percent methane.[63] For energy

[63] About 70 percent of landfill waste contains organic material including yard waste, household garbage, food waste, and paper. Landfill gas production typically begins one or two years after waste placement and may last for decades. Site-specific factors such as waste quantity and composition, moisture, temperature, and pH all affect the quantity of the landfill gas produced.

production the important gas is methane. Landfill methane is typically flared. However, interest in the use of landfill gas to fuel electricity generation is growing. Nationally, nearly three-quarters of landfill gas recovery projects use internal combustion engines to generate electricity. The remaining projects use gas or steam turbines (17 and 7 percent, respectively). The internal combustion engines are primarily used in plants producing up to 5,000 kW, while turbines are used in the larger projects.

As a greenhouse gas, methane emissions from landfills were estimated in the WSEO greenhouse gas inventory. Landfills in Washington are projected to produce 407,600 tons of methane in 2010. Landfill regulations are becoming more stringent and now requirements include installation of leachate collection systems to prevent liquids from entering the ground water and landfill gas collection systems. WSEO projects that the collection system will capture about 75 percent or 305,700 tons of methane. At a conversion rate of 9.4 aMW/trillion Btu for internal combustion engines, landfill methane could produce about 140 aMW of electricity in 2010.

Since the landfill gas is “free” and regulations require gas collection systems for environmental reasons, the cost of this electricity is limited to generator - engines and associated equipment. EPA estimates the capital cost of landfill gas electric generating systems at $1,200/kW. Amortizing the capital costs over twenty years and assuming an 80 percent capacity factor results in a $0.0137 cost per kWh. The operating and maintenance costs are about $0.015/kWh. Altogether, the cost of electricity generated with landfill gas is estimated at about $0.029 per kWh—comparable to the cost of electricity from natural gas combustion turbines. Therefore, the carbon dioxide control cost effectiveness of landfill gas combustion is assumed to be near $0 per ton. After accounting for the benefits of methane reduction and assuming all 140 aMW of potential electricity is realized, then carbon dioxide emissions fall by about 494,000 tons in 2010.

***Types Of Digestor Systems***

There are three types of digestor systems. Covered lagoons—the simplest recovery system—consists of a manure collection system, a solids separator, a lagoon, a water withdrawal system, and an electric generating system. A rubberized cover is floated on top of the lagoon. A piping system collects the methane and delivers it to an engine-electricity generator.

A plug flow digestor system includes manure delivery, a long air-tight trough, effluent removal and methane collection. Each day a new “plug” of manure is added at one end of the trough. This slowly pushes the other manure down the trough. An air tight cover maintains anaerobic conditions. The gas is collected through a perforated pipe above the manure and transported to an engine generator.

Complete mix digestors are similar in concept to the plug flow digestor. The difference is the circular shaped digestor vessel. Waste heat from the engine cooling system warms the vessel and the manure is mechanically mixed in the digestor. Complete mix digestors typically handle a lower solid content manure than plug flow digestors and generally handle larger manure volume.

Animal Manure is another source of methane gas produced through anaerobic digestion. The quantity of methane produced from animal manure depends on the type and number of animals, the manure generation rate, and the manure management system. Manure management systems are classified as solid systems and liquid systems. Solid systems include animals on pasture or range, dry collection as done on feedlots, and solid storage. Solid management systems produce only five percent of the gas that could theoretically be produced from the manure. Liquid systems produce up to 65 percent of the theoretical potential. Liquid systems include liquid or slurry collections, pit storage and anaerobic lagoons. Animal manure anaerobic digestor systems are not a mature technology, only 24 operate on farms in the United States.

The type of methane recovery system used depends upon the farm size, number of animals, manure management system characteristics, climate, and farm electricity needs. Table 21 shows typical capital and operating costs for the three types of digestor systems for three farm sizes.

**TABLE 21**
**Capital and Operating Costs for Animal Waste to Electricity Generating Systems**

| Digestor Type | Farm Size (head) | Capital Costs | Annual O& M Costs |
|---|---|---|---|
| **Lagoon** | 250 | $69,500 | $2,100 |
| | 500 | $99,800 | $4,200 |
| | 1,000 | $163,800 | $8,500 |
| **Plug Flow** | 250 | $97,800 | $1,100 |
| | 500 | $130,100 | $2,200 |
| | 1,000 | $190,300 | $4,400 |
| **Complete Mix** | 250 | $117,400 | $1,500 |
| | 500 | $168,200 | $3,100 |
| | 1,000 | $261,800 | $6,100 |

Dairy cows provide the major recoverable animal manure resource in Washington. In 1992 the manure generated by about 242,000 dairy cows had the potential to produce 26 aMW of electric power. The generating potential is based on the rule of thumb of slightly more than 0.1 aMW per thousand head of dairy cows. The economics of generation depend on heard size. From the capital and operating costs of Table 21, a cost per kWh of 0.039 and 0.041 is estimated for herd sizes of 1500 and 750 head, respectively. Assuming a size cut off of 750 head, then a 5.5 MW generation potential exists. The climate change benefits of this strategy go beyond displacing electricity from other generating sources. It also reduces methane emissions, a potent greenhouse gas.. Altogether an estimated <u>110,000 ton reduction in equivalent carbon dioxide</u> gas emissions at a cost of $1.72 per ton will result from manure methane recovery and electricity generation at farms with 750 head.

## Carbon Sequestration

Geoengineering is an alternate approach to respond to the effects of global climate change. Rather than limit emissions, geoengineering options are designed to capture carbon dioxide from the atmosphere or block some sunlight from reaching the earth. According to the National Academy of Sciences, potential geoengineering options include screening sunlight and increasing carbon dioxide uptake in oceans and forests (see Tabel 22).

TABLE 22

**Carbon Sequestration Profile†**

| Geoengineering Option | Geoengineering Option Implementation | Cost | Emission Mitigation ($CO_2$ Equivalent tons per year) |
|---|---|---|---|
| Low stratospheric soot | Decrease efficiency of burning in engines of aircraft flying in the low stratosphere to maintain a thin cloud of soot to intercept sunlight | Low | 8 billion to 25 billion |
| Low stratospheric dust<br>• aircraft delivery<br>• balloon/gun delivery | Use aircraft, guns or balloons to create and maintain a dust cloud in the stratosphere to increase sunlight reflection. | Low | 8 billion to 4 trillion |
| Cloud stimulation | Burn sulfur in ships or power plants to form sulfate aerosols in order to stimulation additional low marine clouds to reflect sunlight. | Low | 4 trillion or amount desired |
| Stratospheric bubbles | Place billions of aluminized, hydrogen-filled balloons in the stratosphere to provide a reflective screen. | Low to moderate | 7 billion or amount desired |
| Stimulate ocean biomass | Place iron in the oceans to stimulate generation of carbon dioxide absorbing phytoplankton. | Low to moderate | 4 trillion or amount desired |
| Space mirrors | Place 50,000 10-$km^2$ mirrors in earth orbit to reflect incoming sunlight. | Low to moderate | 4 trillion or amount desired |
| Reforestation | Reforest 28.7 Mha of economically or environmentally marginal crop and pasture lands and nonfederal forests. | Low to moderate | |

† From Policy Implications of Greenhouse Warming, National Academy Press, 1991. An option has a low cost if its costs less than $10 per ton of carbon dioxide equivalent, a moderate cost is between $10 and $100 per ton of carbon dioxide equivalent.

**Afforestation.** One obvious carbon dioxide sequestration practice is to plant idle cropland with trees. The 1992 Department of Commerce Agricultural Census found about 450,000 acres of idle cropland in Washington and 1.7 million acres in summer fallow (see Table 23).[64]

Birdsey estimates that newly planted Pacific coast forests sequester 12.2 tons of carbon dioxide per acre. Assuming only idle cropland is available for afforestation, the new forests could annually sequester 5.5 million tons of carbon dioxide. Moulton and Richards estimate the cost of planting trees at $180 per acre and renting idle cropland at $42 per year.[65] The cost effectiveness of afforestation is approximately $4.20 per ton of carbon dioxide sequestered.

TABLE 23

**Unused farmland in Washington, 1992 (acres)†**

| Eastern | Idle | Summer | Western | Idle | Summer |
|---|---|---|---|---|---|

[64] Idle cropland may be uneconomic to farm or participate in federal farm setaside programs. The Commodity Acreage Adjustment program diverts cropland from production of wheat, cotton, corn, sorghum, and barley into conservation uses. The Conservation Reserve Programs or Wetlands Reserve Programs take highly erodible land out of production and reforest or plant with protective cover crops. Alig et. al. reports that up to two million acres of Pacific Northwest idle cropland (Washington and Oregon) may revert to natural cover.

[65] Representatives of the State Department of Natural Resources (Dennis Carlson, personal communication) and the Weyerhaeuser Corporation (John McMahon, personal communication) indicated that a $180 per acre reforesting cost was “in the ballpark” but could be higher. Variables affecting the cost of planting stock include, the number of trees per acre, labor costs, land characteristics (steep slopes, inaccessible areas) and the cost to prepare the land. Since cropland is generally relatively flat and smooth, I assume the $180 per acre estimate is reasonable.

| Counties | Cropland | Fallow | Counties | Cropland | Fallow |
|---|---|---|---|---|---|
| Adams | 52,101 | 263,626 | Clallam | 181 | 84 |
| Asotin | 4,806 | 22,649 | Clark | 880 | 461 |
| Benton | 26,054 | 137,287 | Cowlitz | 504 | 60 |
| Chelan | 3,520 | 1,197 | Grays Harbor | 388 | 88 |
| Columbia | 13,212 | 54,955 | Island | 657 | 177 |
| Douglas | 50,403 | 186,343 | Jefferson | 163 | 0 |
| Ferry | 1,566 | 1,304 | King | 868 | 38 |
| Franklin | 40,532 | 87,854 | Kitsap | 450 | |
| Garfield | 14,603 | 56,676 | Lewis | 1,720 | 248 |
| Grant | 42,047 | 118,315 | Mason | | |
| Kittitas | 3,725 | 4,657 | Pacific | 242 | |
| Klickitat | 11,803 | 42,267 | Pierce | 1,285 | 190 |
| Lincoln | 45,371 | 301,531 | San Juan | 392 | 6 |
| Okanogan | 13,558 | 7,136 | Skagit | 1,092 | 468 |
| Pend Oreille | 411 | 296 | Skamania | | 0 |
| Spokane | 14,532 | 35,249 | Snohomish | 1,205 | 151 |
| Stevens | 3,782 | 11,707 | Thurston | 1,534 | |
| Walla Walla | 34,983 | 176,827 | Wahkiakum | | 0 |
| Whitman | 44,397 | 227,095 | Whatcom | 1,998 | 536 |
| Yakima | 21,732 | 30,224 | | | |
| **Total** | **443,138** | **1,767,195** | | **13,559** | **1,971** |

† Blank entries indicate data unknown or not available. From 1992 Agricultural Census.

‡ Excerpted from Policy Implications of Greenhouse Warming, National Academy Press, 1991.

This analysis ignores two important factors which will affect the price of carbon sequestration. First, cropland rental rates will vary depending on alternative uses. Idle land near growing

**What Happens to Carbon in a Forest?‡**

There are two principal phases to the plant energy production/consumption cycle. During the photosynthesis phase, plants use sunlight to convert water and carbon dioxide into energy containing organic compounds. During the second or dark phase, plants consume the energy stored in these compounds and respire carbon dioxide. The balance favors the net accumulation of carbon in trees, shrubs, herbs, and roots. The rate of carbon storage in an ecosystem is known as net productivity. Young, vigorous forest stands tend to exhibit the greatest growth rates. However, total carbon stored at any time is greatest in older, mature forests, even though they have a net growth rate near zero. Much of the carbon in older forests is hidden - as much as 60 percent of the carbon in forests is stored below ground in organic matter (including roots) and organisms in the soil.

The effect of cutting forests on atmospheric carbon dioxide depends on how much carbon was stored in the forest, what happens to the cut wood, and how the lands are managed. Cut wood left on site decomposes. Microorganisms (e.g., fungi, bacteria) consume it, along with leaf and branch litter. Through their metabolic activities, microorganisms convert carbon in the wood to carbon dioxide. Decomposition rates depend on factors such as oxygen availability, temperature, and moisture. Burning wood directly emits carbon dioxide. In some cases, though, wood fuel can replace traditional fossil fuels; over one-half of the wood removed from U.S. forests in the early 1980's was burned for energy. The net effect on carbon dioxide depends on combustion efficiency, the alternate fossil fuel, and carbon storage rates of vegetation that replaces the trees.

Finished wood products store carbon until they decompose. Durable products such as construction lumber retain carbon for decades or even centuries; about one-fourth of stemwood harvested during the last 35 years has been converted to such products. Short-lived products such as paper may decompose and release carbon dioxide or methane quickly after being discarded. Carbon release rates depend on the conditions at the discarded site.

After harvesting, carbon dioxide is again taken in by new vegetation growing on the site, assuming the land is not converted to nonegative state. The net offset in carbon dioxide emissions from the harvesting depends on the type of vegetation (e.g., crops, pasture, or trees), the rate at which it and the soil stores carbon, the availability of nutrients, and how long the vegetation grows before being harvested again. If the time scale is long enough, the land is used for a series of harvests, and the harvested wood is converted into durable products or displaces fossil fuels, then forests can be a net sink for carbon.

communities is likely to have high costs due to its potential use for residential development. Alternatively, remote areas lacking viable alternatives will have very much lower rental costs.

Since most of Washington's idle cropland is located in the relatively more rural eastern half the of state, we expect that Moulton and Richards' estimated rental rate is reasonable. The second important factor is whether the planted trees would be harvested. Data from Adams et. al., suggests that allowing harvesting improves the overall cost effectiveness of afforestation by half (e.g., $2.10 per ton). Adams suggests that the market for timber products is relatively inelastic so that increasing the supply provides a substantial price benefit to consumers.

**Other Geoengineering Options.** After afforestation, the geoengineering alternative receiving the most attention is ocean iron fertilization. Surface waters of over 20 percent of the world's oceans have minimal levels of phytoplankton despite containing the major plant nutrients (nitrate, phosphate and silicate). Some suggest iron—important for a wide variety of electron transport and enzymatic systems—is the limiting factor (Martin et. al., Kolber et. al., Scoy and Coale). de Baar et. al., reported that the mass of spring phytoplankton blooms in the Southern Ocean varied by an order of magnitude between iron rich waters (more biomass) and iron poor waters. Tests found that plant mass doubled, chlorophyll levels tripled and plant production increased four fold as a result of adding iron to the ocean. However, these increases were seen to subside somewhat over time. Joos et. al., estimate that a continuous iron fertilization effort could annually remove 2.6 billion tons of carbon dioxide from the atmosphere.

Emplacing dust in the stratosphere is also a potential option for reducing the effects of increased atmospheric carbon dioxide levels. In a study of Mt. Pinatubo, McCormick et. al. estimate that for 1991 and 1992, the cooling effect of the aerosols thrown up by the eruption overwhelmed the warming expected from the combined anthropogenic emissions of all greenhouse gasses. In 1992, radiative forcing of the aerosols was calculated at -3 $W/m^2$.

However, while geoengineering measures have the potential to substantially affect global climate, our limited understanding of the global climate system make the ultimate effects of such measures highly uncertain. Moreover, some have the potential to cause other adverse environmental consequences. The very nature of these measures make them more appropriate for a national or international debate.

## CONCLUSIONS

Global climate change poses a serious dilemma for policy makers. The likelihood, timing and results of climate change are uncertain. And these uncertainties will not be resolved for decades, or even centuries. Waiting risks irreversible damages while immediate action risks large expenditures to mitigate inconsequential or even beneficial changes. Addressing global climate change will require the skills of scientists and policy makers: scientists to describe the potential consequences of climate change and alternative mitigation strategies, and policy makers to balance the threats and opportunities of climate change relative to other social needs and desires. This report falls much more in the former camp; describing the potential consequences of climate change and alternative mitigation strategies. However, we part with a few thoughts on how the policy maker might take this information to develop a response strategy.

Manne and Richels suggest that policy makers consider greenhouse gas mitigation measures as an insurance policy against an uncertain future. Using decision theory techniques, they demonstrate the amount of precaution needed is inversely related to the confidence in a near term scientific consensus regarding the consequences of climate change. Though the IPCC is vastly improving our understanding of the global climate system, it is doubtful that a scientific consensus will soon emerge. Thus, following Manne and Richels' logic, an active program to reduce greenhouse gas emissions is warranted as insurance against our ignorance about climate change. On the other hand, Parry concluded that *"the insurance value from cutting [greenhouse gas] emissions is trivial, relative to the cost.…[because] the possibility of climate change is (a) so far into the future."* Using this logic little effort should be expended to lower carbon dioxide emissions.

Another policy approach to climate change is the "precautionary principle" defined by the 1992 Australian Intergovernmental Agreement on the Environment (Dovers). The central premise of the principle is that one should anticipate and act to prevent serious environmental damage.

> *Where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation. In the application of the precautionary principle; public and private decisions should be guided by:*
>
> *1. [a] careful evaluation to avoid, wherever practicable, serious or irreversible damage to the environment; and*
>
> *2. an assessment of the risk-weighted consequences of various options.*

The principle institutionalizes caution. It recognizes that clear yes-no answers are rarely available and that decisions must be made in the face of uncertainty. Unfortunately, the principle does not define how cautious policy makers should be. Therefore, a response global to warming using the precautionary principle will be far more a moral and political issue than a scientific one.

Lesser and Dodds frame the global climate change issue in terms of our obligation to future generations. *"Broadly speaking, our actions today should not harm or increase risks to future generations. We should be fair to future generations by not denying them the <u>opportunity</u> to be at least as well off as we are because of our actions. We should also pass on our institutions and values. Finally, we should pass on specific assets that are important to our way of life, much as past generations passed on to us."* One difficulty with this approach is how widely to define harm. For example, we clearly will pass on to our children more advanced medical capabilities than our parents passed on to us. Should, or should not this fact balance part of the environmental damage we cause. A second difficulty with this approach involves guessing what assets future generations will value. Some of the assets we pass on will be highly valued while others will not. Unfortunately, there is no way to know which category an asset will fall into.

The OTA (1991) argues the need for mitigation measures given the length of time greenhouse gas emissions will affect the climate.

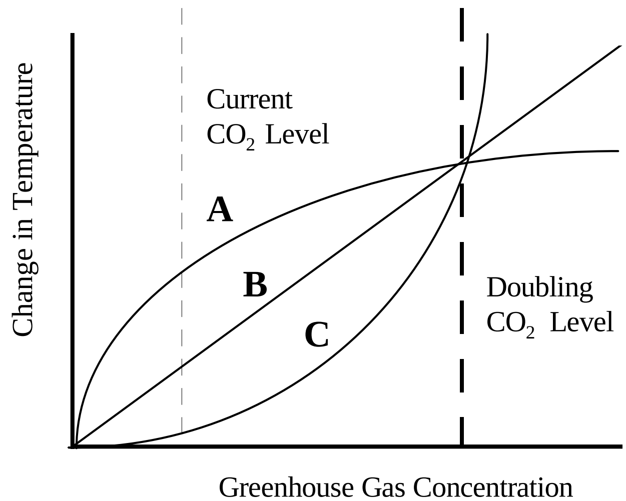
> *We cannot yet predict the magnitude of climate effects from greenhouse gas emissions with accuracy. <u>But it is clear that the decision to limit emissions cannot await the time when the full impacts are evident</u>. The lag time between emission of the gasses and their full impact is on the order of decades to centuries; so too is the time needed to reverse any effects. Today's emissions thus commit the planet to changes well into the 21st century. And the lag times between identification of policy options, legislation of controls, and actual implementation can also be considerable. For example, the recent re-authorization of the Clean Air Act took 10 years; implementation of the Act will begin now and continue over the next 10 to 20 years. (emphasis added)*

Another factor critical to greenhouse gas mitigation decisions is expectation about future technological capabilities. One who is a technology optimist envisions a future where abundant low-cost, carbon free renewable resources supply energy to highly efficient end-use technologies. There is little need for immediate cutbacks since future generations will need little help in adapting to a carbon constraint. The pessimist foresees a society heavily dependent on carbon-intensive synthetic fuels. For this person, it makes sense to begin carbon dioxide abatement now.[66]

An additional consideration is how climate responds to rising greenhouse gas levels. Figure 3 demonstrates three hypothetical response paths. For path "A" temperatures initially rise quickly with increasing carbon dioxide levels and then levels off.[67] Path "C" is just the opposite. The temperature affect accelerates as greenhouse gas levels rise. Path "B" assumes temperature responds linearly to elevated greenhouse gas levels. The effect of greenhouse gas mitigation strategies will vary significantly depending on which response path climate change follows.

**FIGURE 3**

**Alternative Temperature Responses to Rising Greenhouse Gas Concentrations**




Assume the globe is committed to a greenhouse gas level denoted by the light dashed line. If temperatures follow path "A," then most of the temperature rise is a *feit accomplis* and aggressive action to reduce greenhouse gas emissions is probably not warranted. A temperature response along path "C" where each successive unit of emissions has a larger effect indicates a need for heroic efforts to reduce emissions. Path "B" is the most difficult to determine the right amount of control. Here, projections of the consequences of climate change will likely determine the appropriate response. Unfortunately, the path which climate change follows is not known. An additional consideration is that the temperature path of climate change does not necessarily give a good indication of the environmental consequences. The consequences of climate change likely increase faster than temperature—a 2 to 3°C rise in temperature is more significant than a rise from 1 to 2°C.

This situation is not an easy one for policy planners. As stated above, waiting risks irreversible damages while immediate action risks large expenditures to mitigate potentially inconsequential changes. At this point the appropriate response is not clear. Nevertheless, drawing upon the discussion above, this report offers the following framework for policy makers developing a response to global climate change:

1. Actively purse those mitigation strategies that are cost effective for reasons other than their greenhouse gas reduction benefits.

---

[66]From Manne A. and R. Richels, Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits, The MIT Press, 1992.

[67] Ramanathan reports that at 300 ppm carbon dioxide is *"optically thick, and hence its greenhouse effect scales logarithmically with concentration."* What this means is that radiative forcing diminishes as concentrations rise. This does not necessarily mean, however, that the effect on temperature also diminishes. Global temperature change depends on the complexities of climate feedbacks as well as changes in radiative forcing .

2. Efforts to reduce greenhouse gas emissions are investments in the future of the state and nation. As an investment, the mitigation program must compete with other claims on state resources (e.g., education, welfare programs, police and fire protection, etc.)
3. The use of cost effectiveness criteria to develop a mitigation program is essential. Changes in energy, industrial, land use, agriculture, and forestry practices range from cost savings to very expensive. Obtaining the largest emission reduction at the lowest cost is sensible.
4. The expected consequences of global climate change should drive the scope and stringency of a mitigation program.
5. Any mitigation program should consist of a diverse portfolio of programs to protect against unexpected economic and emission effects.
6. Given the uncertainties surrounding climate change, the state should consider carbon dioxide controls as insurance against as yet unknown consequences.
7. The state should commit to better understand the effects of climate change and to further develop greenhouse gas mitigation options. A better understanding of climate change reduces the need to hedge against the uncertainty and improved conservation technologies will enhance our ability to deal with surprises should they occur.

Finally, with regard to specific concerns within Washington perhaps the best policy makers can do is to identify and develop response plans for those activities/environments most sensitive to climate change. In this way the state can help minimize adverse climate change consequences should they come about.

# Bibliography:


Adams, D., Future Prospects for Western Washington's Timber Supply, College of Forest Resources, University of Washington, 1992.

Adams, R., et. al., "Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets," Contemporary Policy Issues, Western Economic Association International, Volume XI, Winter 1993, pp. 76-87.

Agee, J., Fire and Weather Disturbances in Terrestrial Ecosystems of the Eastern Cascades, U.S. Department of Agriculture, Forest Service, PNW-GTR-320, 1994.

Alig, R., et. al., Changes in Area of Timberland in the United States, 1952-2040, by Ownership, Forest Type, Region, and State, U.S. Department of Agriculture, Forest Service, SE-64, 1990.

Anderson, V., Energy Efficiency Policies, Routledge Press, 1993.

Apogee Research Inc., Cost and Effectiveness of Transportation Control Measures: A Review and Analysis of the Literature, Prepared for the National Association of Regional Councils, 1994.

Austin, T., et al., Analysis of the Effectiveness and Cost-Effectiveness of Remote Sensing Devices, Report No. SR94-05-05, May 18, 1994.

Automotive Consulting Group, Low Emission/Ultra Low Emission Vehicles: A Systems Cost Analysis, 1993.

de Baar, H., et. al., "Importance of Iron for Plankton Blooms and Carbon Dioxide Drawdown in the Southern Ocean," Nature, Volume 373, February 2, 1995, pp. 412-415.

Bazzaz, F. and Fajer, E., "Plant Life in a $CO_2$- Rich World," Scientific American, Volume 266, January 1992, pp. 68-74.

Battelle Laboratories, Effects of Climate Change on Pacific Northwest Water-Related Resource: Summary of Preliminary Findings, Unpublished Report.

Baylon, D., et. al, Energy Conservation in Public Buildings, Ecotope, 86-60-104, 1990

Bekki S., Law, K. and Pyle, J., "Effect of Ozone Depletion on Atmospheric $CH_4$ and CO Concentrations," Nature, Volume 371, October 13, 1994, pp. 595-597.

Benton, M., "Diversification and Extinction in the History of Life," Science, Volume 268, April 7, 1995, pp. 52-58.

Birdsey, R., "Changes in Forest Carbon Storage from Increasing Forest Area and Timber Growth, within Forests and Global Change," Volume 1: Opportunities for Increasing Forest Cover, Sampson, R. et. al. editors, American Forests, Washington DC, 1992.

Bisio, A. and Boots, S., Encyclopedia of Energy Technology and the Environment, Volume 2, John Wiley and Sons, 1995.

Brinner et. al., Optimizing Tax Strategies to Reduce Greenhouse Gases Without Curtailing Growth, publication unknown

Byers, R. et. al., Energy Efficiency Resources in Existing Residences Served by Natural Gas in Washington State, Washington State Energy Office, WAOENG-91-02, 1990.

Byers, R., "Environmental Benefits of Energy Efficiency: Impact of Washington State Residential Energy Codes on Greenhouse Gas Emissions," Submitted for publication in ACEEE Proceedings from Summer Study on Energy Efficiency in Building, 1990.

Cahill, R., Results of Staff Assignments Concerning Natural Gas, Memorandum to Jim Waldo, Washington State Energy Strategy Task Force, May 5, 1992.

California Air Resources Board, Proposed Regulations for Low-Emission Vehicles and Clean Fuels: Technical Support Document, 1990.

Cameron, Michael W., "Efficiency and Fairness on the Road: Strategies for Unsnarling Traffic in Southern California," Environmental Defense Fund, 1994.

The Center for Clean Air Policy, The Road from Rio: European Initiatives for Cutting Greenhouse Gas Emissions from the Transportation and Energy Sectors, April 1993.

Charlson, R. et. al., "Climate Forcing by Anthropogenic Aerosols," Science, Volume 255, January 24, 1992, pp. 423-430.

Charlson, R. and Wigley, T, "Sulfate Aerosol and Climate Change," Scientific American, Volume 270, Number 2, February 1, 1994, pp. 48-57.

Ciliano, R., et. al., Impact of Appliance Efficiency Standards And Building Codes on Global Climate Change, publication unknown.

Cline, W., The Economics of Global Warming, Institute for International Economics, 1992.

Clinton, W. and Gore, A., The Climate Change Action Plan, The White House, 1993.

U.S. Department of Commerce, American Housing Survey for the Seattle-Tacoma Metropolitan Area in 1991, Bureau of the Census, , H170/91-60, 1993.

---------------, 1992 Census of Agriculture, Volume 1, Geographic Area Series, Part 47 Washington State and County Data, Bureau of the Census.

---------------, 1982 Census of Manufactures, Fuels and Electricity Consumed, MC82-S-4 (Part 2), 1983.

Cook, E., "Lifetime Commitments: Why Climate Policy-Makers Can't Afford to Overlook fully Fluoridated Compounds," Issues and Ideas, World Resources Institute, February 1995.

Culotta, E., "Will Plants Profit From High $CO_2$," Science, Volume 268, May 5, 1995

Daniel, J., et. al., "On the Evaluation of Halocarbon Radiative Forcing and Global Warming Potentials," Journal of Geophysical Research, Volume 100, Number, D1, January 20, 1995, pp. 1271-1285.

Darmstadter J. and Jones, A., Prospects for Reduced $CO_2$ Emissions in Automobile Transport, Resources for the Future, ENR90-15, 1990.

Davies, T., "An Introduction, The Greenhouse Effect: What Can We Do About It?," EPA Journal, U.S. Environmental Protection Agency, Volume 16, Number 2, March/April 1990, pp. 2-3.

Davis, S. and Strang, S., Transportation Energy Data Book: Edition 13, Oak Ridge National Laboratory, U.S. Department of Energy, ORNL-6743, 1993.

Davis, S., Transportation Energy Data Book: Edition 14, Oak Ridge National Laboratory, U.S. Department of Energy, ORNL-6798, 1994.

Davis, W., et. al., Feebates: Estimating Impacts on Vehicle Fuel Economy, Fuel Consumption, CO2 Emissions, and Consumer Surplus, Draft Report, Lawrence Berkeley Laboratory, 1993.

Decicco, J., Geller, H. and Morrill, J., Feebates for Fuel Economy: Market Incentives for Encouraging Production and Sales of Efficient Vehicles, American Council for an Energy-Efficient Economy, May 1993.

Dessens, J., "Severe Convection Weather in the Context of a Nighttime Global Warming," Geophysical Research Letters, Volume 22, May 15, 1994, pp.1241-1244.

Dobson, A. and Carper, R., "Biodiversity," The Lancet, 1994.

Dodds, D., Compressed Natural Gas as a Vehicle Fuel, The Washington State Energy Office, WSEO 92-129, 1993.

Dornbusch, R. and Poterba, J., Global Warming: Economic Policy Responses, MIT Press, 1991.

Douglas, J., "Understanding the Global Carbon Cycle," EPRI Journal, July/August, 1994, pp. 35-41.

Dovers, S., "Ignorance, the Precautionary Principle and Sustainability," Ambio Volume 24, Number 2, March 1995, pp. 92-97.

Drennen, T. and Chapman D., "Negotiating a Response to Climate Change: Role of Biological Emissions," Contemporary Policy Issues, Western Economic Association International, Volume X, 1992.

DRI/McGraw-Hill, Assessing the Economic Effects of Eastern States Adopting California's Low Emission Vehicle Program, American Petroleum Council, 1991.

Eamus, D. and Jarvis, P., "The Direct Effects of Increase in the Global Atmospheric $CO_2$ Concentration on Natural and Commercial Temperate Trees and Forests," Advances in Ecological Research, Begon, M., et. al. editors, Academic Press, 1989.

Washington State Department of Ecology, Environment 2010, Global Warming and Ozone Depletion: Comparative Risks for Washington State, 1989.

--------------, A Strategy to Reduce Emissions From Motor Vehicles, Steps 2 and 3, Draft Report, Air Quality Program, 1995

The Economist, "The Once and Future Weather," , April 7, 1990, pp. 95-100.

Electric Power Research Institute, Electric Vehicles; The Beginning of a Bright Future, 1992.

U.S. Department of Energy, The Columbia River System:  The Inside Story, A joint project of the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and Bonneville Power Administration, 1991.

--------------, Energy Conservation Program for Consumer Products, Notice of Proposed Rulemaking, Office of Energy Efficiency and Renewable Energy, Federal Register, 59 FR 10646, 1994.

--------------, Energy Conservation Program for Consumer Products: Energy Conservation Standards for Three Cleaning Products, Advanced notice of Proposed Rulemaking, Office of Energy Efficiency and Renewable Energy, Federal Register, 59 FR 56423, 1994.

Energy Design Update, "Advocacy Group Blasts States with Substandard Building Energy Codes," Volume 15, Number 2, February, 1995.

Energy Research Group, Inc., Carbon Dioxide Reduction Through Electrification of the Industrial and Transportation Sectors, for the Edison Electric Institute, 1989.

Environmental Protection Agency, Adapting to Climate Change:  What Governments Can Do, Office of Policy, Planning and Evaluation, 1991.

--------------, States Workbook, Methodologies for Estimating Greenhouse Gas Emissions, Office of Policy, Planning and Evaluation, 1992.

--------------, States Guidance Document, Policy Planning to Reduce Greenhouse Gas Emissions,(December Draft), Office of Policy, Planning and Evaluation, 1993.

--------------, Preliminary Electric Vehicle Emissions Assessment, Draft Paper, 1994.

Envirosphere Company, Regional Logging Residue Supply Curve Project, Volume 1 and 2, Bonneville Power Administration, Portland, OR, 1986

Eyre, L., Reply to "Supercell Thunderstorms," Weather, Volume 48, 1993, pp. 210-211.

Fleagle, R., "Policy Implications of Global Warming for the Northwest," Northwest Environmental Journal, Volume 7, Number 2, University of Washington, 1991.

Fleagle, R., Global Environmental Change:  Interactions of Science, Policy, and Politics in the United States, Preager Press, 1994.

Francis R. and Sibley, T., "Climate Change and Fisheries: What are the Real Issues," Northwest Environmental Journal, Volume 7, Number 2, University of Washington, 1991.

Francey, R., et. al., "Changes in Oceanic Terrestrial Carbon Uptake Since 1982," Nature, Volume 373, January 26, 1995, pp. 326-330.

Frankel, M., et. al., Residential Energy Conservation Evaluation, Cost Effectiveness of Energy Conservation Measures in New Residential Construction in Washington State, Draft Final Report, Ecotope, 1995.

Franklin, J. et. al., "Effects of Global Climate Change on Forests in Northwestern North America," Northwest Environmental Journal, Volume 7, Number 2, University of Washington, 1991.

Gaines, L., and Stodolsky, F., Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume, Air and Waste Management Association, 1994, 94-WA82.04.

U.S. General Accounting Office, GEOTHERMAL ENERGY: Outlook Limited for Some Uses but Promising for Geothermal Heat Pumps, GAO/RCED-94-84.

Gilli, P., et. al., The Impact of Heat Pumps on the Greenhouse Effect, Analysis Report, IEA Heat Pump Centre, HPC-AR1, 1992.

Giorgi, et. al., "Regional Climate Change Scenarios of the United State Produced with a Nested Regional Climate Model," Journal of Climate, Volume 7, Number 3, 1994, pp 375-399.

Graham, R., "Late Pleistocene Fauna Changes as a Guide to Understanding Effects of Greenhouse Warming on the Mammalian Fauna of North America," within Global Warming and Biological Diversity, Peters, R. and Lovejoy, T. editors, Yale University Press, 1992.

Gore, A., Program Updates: White House Conference on Climate Change, Office of the Vice President, 1994.

Gordon D. and Levenson L., Drive+: A proposal for California to use Consumer Fees and Rebates to reduce New Motor Vehicle Emissions and Fuel Consumption, Lawrence Berkeley Laboratory, 1989.

Gould, S., Wonderful Life, The Burgess Shale and the Nature of History, Norton Press, 1989.

Hadaller, O. and Momenthy, A., "Characteristics of Future Aviation Fuels," Transportation and Global Climate Change, D. Greene and D. Santini, Editors, American Council for an Energy-Efficient Economy, 1993.

Harte, J. and Shaw, R., "Shifting Dominance Within a Montana Vegetation Community: Results of a Climate-Warming Experiment," Science, Volume 267, February 10, 1995, pp. 876-879.

Hayes, R. and Hussain, T., "Public Health and Forced Climate Change: Extreme Temperature Exposure and Infectious Disease," World Resource Review, Volume 7, Number 1, 1995, pp. 63-76.

Harness R. et. al., Alternative Simulations of Forestry Scenarios Involving Carbon Sequestration Options: Investigation of Impacts on Regional and National Timber Markets, U.S. Department of Agriculture, Forest Service, PNW-GTR-335, 1994.

Healy, T. and Dick, D., "Total Energy Requirements of the Bay Area Rapid Transit System," Transportation Research Record, No. 552, 1975.

Hillsman F. and Southworth, F., Factors that may Influence Responses of the US Transportation Sector to Policies for Reducing Greenhouse Gas Emissions, Oak Ridge National Laboratory, Energy Division, 1989.

Hogan, W. and Jorgenson, D., "Productivity Trends and the Cost of Reducing CO2 Emissions, Discussion Paper," Global Environmental Policy Project, John F. Kennedy School of Government, Harvard University, 1990.

ICF Incorporated, "Preliminary Technology Cost Estimates of Measures Available to Reduce U.S. Greenhouse Gas Emissions by 2010," 1995.

Information, Inc., 1995 Washington State Yearbook, published in cooperation with the Office of the Governor and the Office of the Secretary of State.

Intergovernmental Panel on Climate Change, Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment, World Meteorological Organization and United Nations Environmental Programme, 1992.

--------------, The IPCC assessment of Knowledge Relevant to the Interpretation of Article 2 of the UN Framework Convention on Climate Change: A Synthesis Report, 1995, Acquired via the Internet at http://www.usgcrp.gov/ipcc/level1/Synth.html, 1995.

Jack Faucett Associates, "Economic Incentives to Reduce Emissions From Mobile Sources: Summary of Drive+ and Other State Programs," JACKFAU 413-7, 1991.

Jacobs, C., Environmental Protection Agency, Personal Communication, 1995.

Joos, F. et. al., "Possible Effects of Iron Fertilization in the Southern Ocean on Atmospheric Carbon Dioxide Concentrations," Global Biogeochemical Cycles, Volume 5, number 2, June 1991, pp. 135-150.

Kalkstein, L., "A New Approach to Evaluate the Impact of Climate on Human Mortality," Environmental Health Perspectives, Volume 96, 1991, pp. 145-150.

Kalkstein, L. and Davis, R., "Weather and Human Mortality: An Evaluation of Demographic and Interregional Responses in the United States," Annals of the Association of American Geographers, The Association of American Geographers, Volume 79, 1989, pp. 44-64.

Kempton, W. et. al., "Global Climate Change: European Policy Makers' Views of How Science Enters the Political Process," Energy & Environment, Volume 6, Issue 2, 1995, pp. 87-105.

Kerstetter, J, Greenhouse Gas Emissions Inventory For Washington State, 1990, Washington State Energy Office, 1994.

--------------, Projected Greenhouse Gas Emissions Inventory For Washington State in 2010, Washington State Energy Office, 1994.

Kimball, B., "Carbon Dioxide and Agriculture Yields: An Assemblage and Analysis of 430 Prior Observations," Agronomy Journal, Volume 75, 1983, pp. 779-788.

Kirshbaum, M. et. al., "Modeling Forest Response to Increasing CO2 Concentration Under Nutrient-Limited Conditions," Plant, Cell and Environment, Volume 17, 1994, pp. 1081-1099.

Kolber, Z., et. al., "Iron Limitation of Phytoplankton Photosynthesis in the Equatorial Pacific Ocean," Nature, Volume 371, September 8, 1994, pp. 145-148.

Krupnick, A., Walls, M. and Collins, C., Global Warming and Urban Smog: The Cost Effectiveness of CAFE Standards and Alternative Fuels, Resources for the Future, ENR92-13, 1992.

Krupnick, A., Walls, M. and Carter-Hood, H., The Distributional and Environmental Implications of an Increase in the Federal Gasoline Tax, Resources for the Future, ENR93-24, 1993.

Kukla, G. and Karl, T., Nighttime Warming and the Greenhouse Effect, Environmental Science and Technology, Volume 27, Number 8, 1993.

Kunkle, R. and Lagerberg, B., Travel Characteristics and Impacts of Telecommuting, Washington State Energy Office, WSEO 94-247, 1994.

Laitner, S., and Goldberg, M., Energy Efficiency and Renewable Energy as An Investment in Washington's Economic Future, Campaign for an Environmental Economy, 1994.

Lashof, D., "EPA's Scenarios for Future Greenhouse Gas Emissions and Global Warming," The Energy Journal, Volume 12, Number 1, 1991, pp. 125-146.

Lazar, J. and Bell, K., Emission Reduction Options for the Hermiston Generating Project, Convergence Research, 1994.

Lee, D., A Market-Orientated Transportation and Land Use System: How Different Would it Be?, U.S. Department of Transportation, Research and Special Programs Administration, 1992.

Lesser, J. and Byers, R., Cost-Effectiveness of Compact Fluorescent Lighting, Retrofits for Residential Consumers in the Pacific Northwest, Washington State Energy Office, WAOENG-91-06, 1991.

Lesser, J. and Dodds, D., Developing Policies that Address Energy Resources and Climate Change, Executive Summary, State of Washington, Interagency task Force on Environmental Costs, Issue Paper: ITF-4, 1992.

Leverenz, J. and Lev, D., "Effects of Carbon Dioxide-Induced Climate Changes on the Natural Ranges of Six Major Commercial Tree Species in the Western United States," The Greenhouse Effect, Climate Change, and U.S. Forests, Hoffman, J., and Shands, W. editors, The Conservation Foundation, 1987.

Lewandrowski, J. and Brazee, R., "Government Farm Programs and Climate Change: A First Look," Economic Issues in Global Climate Change: Agriculture, Forestry, and Natural Resources, Reilly, J., and Anderson, M. editors, Westview Press, 1992.

Lighthill, J., et. al., "Global Climate Change and Tropical Cyclones," Bulletin of the American Meteorological Society, Volume 75, Number 11, November, 1994, pp. 2147-2157.

Lyman F. et. al., The Greenhouse Trap: What We're Doing to the Atmosphere and How We Can Slow Global Warming, World Resources Institute, 1990.

MacKenzie, The Keys To The Car, Electric an Hydrogen Vehicles for the 21st Century, World Resources Institute, 1994.

MacKenzie, J. and Walsh, M., DRIVING FORCES: Motor Vehicle Trends and Their Implications for Global Warming, Energy Strategies, and Transportation Planning, World Resources Institute, 1990.

Manne, A. and R. Richels, Buying Greenhouse Insurance: The Economic Costs of Carbon Dioxide Emission Limits, The MIT Press, 1992.

Martin, J., et. al., "Testing the Iron Hypothesis in Ecosystems of the Equatorial Pacific Ocean," Nature, Volume 371, September 8, 1994, pp. 123-129.

Maycock, P., "Photovoltaic Technologies, A History and Forecast, 1975-2000," Solar Today, The American Solar Energy Society, Volume, 9, Number 6, Nov/Dec 1995, pp. 26-29.

McCormick, M., et. al. "Atmospheric Effects of the Mt. Pinatubo Eruption," Nature, Volume 373, February 2, 1995, pp. 399-404.

McCoy, G., Kerstetter, J., and Lyons, K., Alcohol-Fuels Vehicle, The Washington State Energy Office, WSEO 93-125, 1993.

McCoy, G. and Lyons, K., Electric Vehicles, An Alternative Fuels Vehicle, Emissions, and Refueling Technology Assessment, The Washington State Energy Office, WSEO 93-123, 1993.

--------------, Procuring Clean Burning Vehicles for the Washington State Fleet—1993 Results and the 1994 Approach, The Washington State Energy Office, 1994.

McCoy, G. et. al., Lost Opportunities for Electrical Generation: A Resource Assessment for Washington State, The Washington State Energy Office, WAOENG-87-06/1, 1987.

McKenny, M. and Rosenberg, N., Simulating the Impacts of Climate Change on Potential Evapotranspiration: A Comparison of the Climate Sensitivity of Selected Methods, Resources for the Future, 1991.

Mearns, L. et al., "Climate Forecasting," Climate Change and U.S. Water Resources, Waggoner, P. editor, American Association for the Advancement of Science, John Wiley & Sons, 1990.

Meese, D. et. al., "The Accumulation record from the GISP2 Core as an Indicator of Climate Change Throughout the Holocene," Science, Volume 266, December 9, 1994, pp. 1680-1682.

Melillo, J. et al., "Global Climate Change and Terrestrial Net Primary Production," Nature, Volume 363, Number 6426, May 20, 1993, pp. 234-240.

Miles-McLean, R., Haltmaier, S. and Shelby, M., Designing Incentive-Based Approaches to Reduce Carbon Dioxide Emissions From the Light-Duty Vehicle Fleet.

Moulton R. and Richards, K., Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States, U.S. Department of Agriculture, Forest Service, WO-58, 1990.

Myers, J. and Lester, R., "Double Jeopardy for Migrating Animals: Multiple Hits and Resource Asynchrony," within Global Warming and Biological Diversity, Peters, R. and Lovejoy, T. editors, Yale University Press, 1992.

National Academy Press, Policy Implications of Greenhouse Warming, 1991.

Nadel, S., et. al., Emerging Technologies to Improve Energy Efficiency in the Residential and Commercial Sectors, American Council for an Energy-Efficient Economy, 1993.

Nadis, S., A Flashy Global Thermometer, Technology Review, January 12, 1993.

Neitzel, D. et. al., "The Effect of Climate Change on Stream Environments: The Salmonid Resource of the Columbia River Basin," Northwest Environmental Journal, Volume 7, Number 2, University of Washington, 1991.

Nelson, M., Wind Energy Resource Potential, Draft Report, Washington State Energy Office, 1995.

Nichols, M. et. al., "Possible Human Health Impacts of a Global Warming," World Resource Review, Volume 7, Number 1, 1995, pp. 77-103.

Norby R., et al, "Productivity and Compensatory Responses of Yellow-Poplar Trees in Elevated $CO_2$," Nature, Volume 357, May 28, 1992, pp. 322-324.

Nordhaus, W., "The Cost of Slowing Climate Change: A Survey," The Energy Journal, Volume 12, Number 1, 1991, pp. 37-64.

Norman, C., "Greenhouse Policy: A Bargain?," Science, Volume 252, April 12, 1991, pp. 205-206.

Northwest Power Planning Council, 1991 Northwest Conservation and Electric Power Plan, Volume II - Part I, , 91-05, 1991.

--------------, Direct Use of Natural Gas: Analysis and Policy Options, , Draft Report, 94-3, 1994.

Oates, W. and Portney, P., "Economic Incentives and the Containment of Global Warming," Eastern Economic Journal, Volume 18, Number 1, Winter 1992, pp. 85-98.

Ogden, J. and Williams, R., Solar Hydrogen, Moving Beyond Fossil Fuels, World Resources Institute, 1989.

Osborn, D. and Collier, D., Utility Commercialization of Grid-connected Photovoltaics, Solar Program/Energy Efficiency District, Sacramento Municipal District, 1994

Park, R., Lee, J. and Canning, D. Potential Effects of Seal Level Rise on Washington State Wetlands, Indiana University and Washington Department of Ecology for the U. S. Environmental Protection Agency, 1991.

Parks, P. and Hardie, I., "Least-Cost Forest Reserves," Land Economics, Volume 71, Number 1, February 1995, pp. 122-136.

Parry, I., "Some Estimates of the insurance Value Against Climate Change from Reducing Greenhouse Gas Emissions," Resource and Energy Economics, Volume 15, March 1993, pp. 99-115.

The Pennsylvania Low Emission Vehicle Commission, Final Report, 1993.

Peterson, D. and Keller, A, "Irrigation," Climate Change and U.S. Water Resources, Waggoner, P. editor, American Association for the Advancement of Science, John Wiley & Sons, 1990.

Peters, R., "Conservation of Biological Diversity in the Face of Climate Change," within Global Warming and Biological Diversity, Peters, R. and Lovejoy, T. editors, Yale University Press, 1992.

Pickrell, D., "Federal Tax Policy and Employer-Subsidized Parking" within Proceedings of the Commuter Parking Symposium, U.S. Department of Transportation, DOT-T-91-14, 1990.

Pilewskie P. and Valero, F., “Direct Observations of Excess Solar Absorption by Clouds,” Science, Volume 267, March 17, 1995, pp. 1626-1629.

Price, C. and Rind, D., “The Impact of a 2 × $CO_2$ Climate on Lightning-Caused Fires,” Journal of Climate, Volume 7, Number 10, October, 1994, pp. 1484-1494.

Puget Sound Council of Governments, VISION 2020, Growth Strategy and Transportation Plan for the Central Puget Sound Region, Final Environmental Impact Statement, 1990.

Quiad, M. and Lagerberg, B., Puget Sound Telecommuting Demonstration, Executive Summary, Washington State Energy Office, WSEO 92-138, 1992.

Radian Corporation, Emission Reductions and Costs of Mobile Source Controls, Virginia Petroleum Council, 1992.

Rahmstorf, S., “Rapid Climate Transpositions in a Coupled Ocean-Atmospheric Model,” Nature, Volume 327, November 3, 1994, pp. 82-85.

Ramanathan, V., “The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment,” Science, Volume 240, April 15, 1988, pp. 293-299.

Ray, G., et. al., “Effects of Global Warming on the Biodiverstiy of Coastal Marine Zones,” within Global Warming and Biological Diversity, Peters, R. and Lovejoy, T. editors, Yale University Press, 1992.

Reed, M. and Renner, J., “Environmental Compatibility of Geothermal Energy,” Chapter 2 in Alternative Fuels and the Environment, edited by Sterrett, F., Lewis Publishers, 1994.

The Results Center, Madison Gas & Electric, Profile #93.

--------------, Public Service Electric & Gas, Standard Offer Program, Profile # 96.

--------------, Burlington Electric Department Comprehensive Municipal DSM, Profile #98.

--------------, Waverly Light and Power, Comprehensive Municipal DSM, Profile #99.

Revkin, A., Global Warming: Understanding the Forecast, Abbeville Press, 1992.

Rind, D. and Chandler, M., “Increased Ocean Heat Transports and Warmer Climate,” Journal of Geophysical Research, Volume 96, Number D4, April 20, 1991, pp. 7437-7461.

Rodier, C. and Johnston, R., Incentives for Local Governments to implement Travel Demand Management Measures, Institute of Transportation Studies, University of California at Davis, 1994

Rogers, D. and Packer, M., “Vector-Borne Diseases, Models and Global Change,” The Lancet, 1994.

Rosenzweig, C. and Parry, M., “Potential Impact of Climate Change on World Food Supply,” Nature, Volume 367, January 13, 1994, pp. 133-138.

Ruston, J., and Denison, R., Advantage Recycle:  Assessing the Full Costs and Benefits of Curbside Recycling, Environmental Defense Fund, February 1995.

Savage, J. and Lisowski, M., “Strain Measurements and the Potential for a Great Subduction Earthquake Off the Coast of Washington,” Science, Volume 252, April 5, 1991, pp. 101-103.

Schimel, D., “Terrestrial Ecosystems and the Carbon cycle,” Global Change Biology, Volume 1, 1995, pp. 77-91.

Schmidt, J. and Shintani, A., Estimates of Industrial Technical Conservation Potential in the Pacific Northwest, Bonneville Power Administration, 1994.

Scoy, K. and Coale, K., “Pumping Iron in the Pacific,” New Scientist, December 3, 1994, pp. 32-35.

Shoup, D., and Willson, R., “Employer-Paid Parking: The Influence of Parking Prices on Travel Demand” within Proceedings of the Commuter Parking Symposium, U.S. Department of Transportation, DOT-T-91-14, 1990.

Skiles, J. and Hanson J., “Responses of Arid and Semiarid Watersheds to Increasing Carbon Dioxide and Climate Change as Shown by Simulation Studies,” Climate Change, April, 1994, pp. 377-397.

Smith, J. and Tirpak, D., The Potential Effects of Global Climate Change on the United States, Draft Report to Congress, United States Environmental Protection Agency, October 1988.

Scheider, S., Gleik, P. and Mearns, L., “Prospects for Climate Change,” Climate Change and U.S. Water Resources, Waggoner, P. editor, American Association for the Advancement of Science, John Wiley & Sons, 1990.

Schlesinger, M. and Ramnkutty, N., “Implications for Global Warming of Intercycle Solar Irradiance Variations,” Nature, Volume 360, October 26, 1992, pp. 330-333.

Sierra Research Inc., The Cost-Effectiveness of Further Regulating Mobile Source Emissions, 1994.

--------------, Estimate of Motor Vehicle Air Toxics, Phase 1, Memorandum from Philip Heirigs to John Raymond, Washington State Department of Ecology, June 17, 1994.

Standing Committee to Review the Research Program of the Partnership for a New Generations of Vehicles, Review of the Research Program of the Partnership for a New Generations of Vehicles, National Academy Press, 1994.

U.S. Department of State, Materials for the Informal Seminar on U.S. Experience with ‘Comprehensive’ and ‘Emissions Trading’ Approaches to Environmental Policy," Washington D.C., 1990.

Stevens, W., “In Rain and Temperature Data, New Signs of Global Warming,” The New York Times, September 26, 1995, pp. B7.

Stone, P., “Forecast Cloudy: The Limits of Global Warming Models,” Technology Review, February/March 1992, pp. 32-40.

Stone, R., “If the Mercury Soars, So May Health Hazards,” Science, Volume 267, February 17, 1995, pp. 957-958.

Stone, R., “Putting Methane Worries on Ice,” Science, Volume 267, March 3, 1995, pp. 1271-1272.

Sugden, D., “Global Warming: Antarctic Ice Sheet At Risk?,” Nature, Volume 359, October 29, 1992, pp. 775-776.

Tans, P., et. al., “Observational Constraints on the Global Atmospheric $CO_2$ Budget,” Science, Volume 247, March 23, 1990, pp. 1431-1438.

Taubes, G., “Is a Warmer Climate Wilting The Forests of the North?,” Science, Volume 267, march 17, 1995, pp. 1595.

Office of Technology Assessment, Building Energy Efficiency, U.S. Congress, OTA-E-518, 1992.

--------------, Changing by Degrees: Steps to Reduce Greenhouse Gases, U.S. Congress, OTA-O-483, 1991.

---------------, Saving Energy In U.S. Transportation, U.S. Congress, OTA-ETI-589, 1994.

Thompson, G. and Drake, B., “Insects and Fungi on a C3 Sedge and a C4 Grass Exposed to Elevated Atmospheric CO2 Concentrations in Open-Top Chambers in the Field,” Plant, Cell and Environment, Volume 17, Number 10, October, 1994, pp. 1161-1167.

Toumi, R., Bekki S., and Law, K., “Indirect Influence of Ozone Depletion on Climate Forcing by Clouds,” Nature, Volume 372, November 24, 1994, pp. 348-351.

Tracy, C., “Ecological Responses of Animals to Climate,” within Global Warming and Biological Diversity, Peters, R. and Lovejoy, T. editors, Yale University Press, 1992.

Ulberg, C., “Parking Tax Discussion Paper” within Proceedings of the Commuter Parking Symposium, U.S. Department of Transportation, DOT-T-91-14, 1990.

Washington State Department of Transportation, Long Term Impact From $1.00 Increase in Washington State Gasoline Tax, , unpublished report.

The Washington State Energy Office, Highlights of the 1991 Washington State Energy Code, 1991.

---------------, Home Insulation, Fact Sheet, 1992.

Walsh, J., "The Elusive Arctic Warming," Nature, Volume 361, January 28, 1993, pp. 300-301.

Washington Public Power Supply System, WNP-2 Performance Indicator Report, Executive Summary, 1994.

Wigley, T. and Raper, S., "Implications for Climate and Sea-Level of Revised IPCC Emissions Scenarios," Nature, Volume 357, May 28, 1992, pp. 293-300.

Willson, R., Suburban Parking Economics and Policy: Case Studies of Office Worksites in Southern California, National Technical Information Service, U.S. Department of Commerce, FTA-CA-11-0036-92-1, 1992.

Whiteford, W. "Effects of Climate Change on Soil Biotic Communities and Soil Processes," within Global Warming and Biological Diversity, Peters, R. and Lovejoy, T. editors, Yale University Press, 1992.

Woodman, J., "Potential Impact of Carbon Dioxide-Induced Climate Changes on Management of Douglas-Fir and Western Hemlock," The Greenhouse Effect, Climate Change, and U.S. Forests, Hoffman, J., and Shands, W. editors, The Conservation Foundation, 1987.

Van de Water, P., Leavitt, S., Betancourt, J., "Trends in Stomatal Density and 13C/12C Ratios of *Pinus Flexilis* Needles During Last Glacial-Interglacial Cycle," Science, Volume 264, April 8, 1994, pp. 239-242.