CO_2, KYOTO AND ENERGY

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Introduction and Summary

We consider aspects of the atmospheric greenhouse gas, global warming and climate change discussion, including the proposed CO_2 emission reductions of the Kyoto protocol and their effect, as well as the role of energy efficiency. We hope to provide a useful guide to some of the important issues and literature.

The Kyoto Protocol specified that, by the year 2010, the United States should reduce its CO_2 fossil fuel combustion emissions to a level 7% below the CO_2 it produced in 1990 [1-3]. Our present CO_2 emissions are about 18% higher than those in 1990 and are projected to be some 34% higher than the 1990 level in 2010. Thus, in order to meet the Kyoto goal, we would have to cut back 25% from where we are now or 40% from where we are headed in 2010. These would be large changes and, if implemented, could have a significant effect on lifestyle [1, 2].

As might be expected, this subject is very complex. Each “sector” of energy use, for example, transportation, industry, commercial buildings, etc has many processes that produce CO_2, and the degree to which each can be reduced is debatable and somewhat uncertain.

A key factor for CO_2 reduction is cost for changing fuels or switching to new technology. But cost can be hard to pin down or forecast, and costs and usage in different sectors can interact unpredictably. The price of oil fluctuates substantially depending on political factors and the state of OPEC. Reference [1] predicts that natural gas prices will go up as the trend to use gas for power production continues. That price increase, however, makes the use of gas for home heating less attractive, so house owners might be tempted to switch to heating by oil and increase CO_2 production from that source. That would also depend on possible heating oil carbon taxes.

There are uncertainties about: 1) to what extent human-produced CO_2 is causing global climate change; 2) what actions will achieve significant CO_2 reduction and how much they will cost; and 3) the complexity of all CO_2-producing processes and varying needs for different countries and regions of the world. The Kyoto protocol does not put limits on energy growth and C emission by developing countries. Applying the Kyoto reductions to the industrialized West while allowing developing countries to continue on their present course only reduces the 2010 total world C emission by 6.5% from where we are headed without Kyoto. In any case the 2010 global C emissions are projected to be about 26% higher than the 1990 emissions, even with the adoption of the Kyoto Protocol.

However, CO_2 is a greenhouse gas, so we cannot ignore this problem. First, we should encourage individuals and businesses to reduce their energy consumption and CO_2 production by implementing cost-effective, efficient approaches to energy use. Sometimes the public has inadequate knowledge of existing energy-efficiency strategies, so government can play an important role in promoting those approaches with campaigns to improve public awareness. This has been done successfully, for example, in the EPA “Green Lights” program [4, 5].

Also, as has long been the case, the government may opt to invest in certain technologies via subsidies or research grants. How much money is spent on CO_2 reduction will depend on how serious the CO_2 problem is perceived. Depending on the urgency of the CO_2 problem as seen by American society, we can decide on changes of our lifestyle and apply additional resources to R&D, deployment of renewables, development of a hydrogen economy or increased nuclear power (e.g. [6, 7]).

It appears that existing energy-efficient technologies by themselves would not lead to CO_2 reductions that are a substantial fraction of the Kyoto goals. Nevertheless they should be implemented, particularly when they represent a cost advantage over present practice. One good example of such a technology is the trend to install natural-gas-powered combined-cycle electric generation [1]. Gas produces less C per unit energy than coal or oil and the combined-cycle plants have heat-to-electricity efficiencies approaching 60%, compared to 30-40% for conventional fossil fuel generation. Gas-powered generators also save other kinds of pollution, for example, emission of sulfur dioxide from coal-fired generating plants.

CO_2, Intergovernmental Panel on Climate Change [IPCC] and Kyoto

The global warming arguments and their connection to CO_2 are as follows [1, 2].

1. Global temperature is rising.
2. Global temperature is rising because of increasing greenhouse gases.
3. Increasing anthropogenic CO_2 emissions constitute the principal greenhouse gas contribution to global warming.

There is a consensus that global surface mean temperature is rising. The exact role of CO_2 and therefore the human contribution to global warming via greenhouse gas production is less certain. Figures 1 and 2 below show the global temperature rise and the concentration of some greenhouse gases.

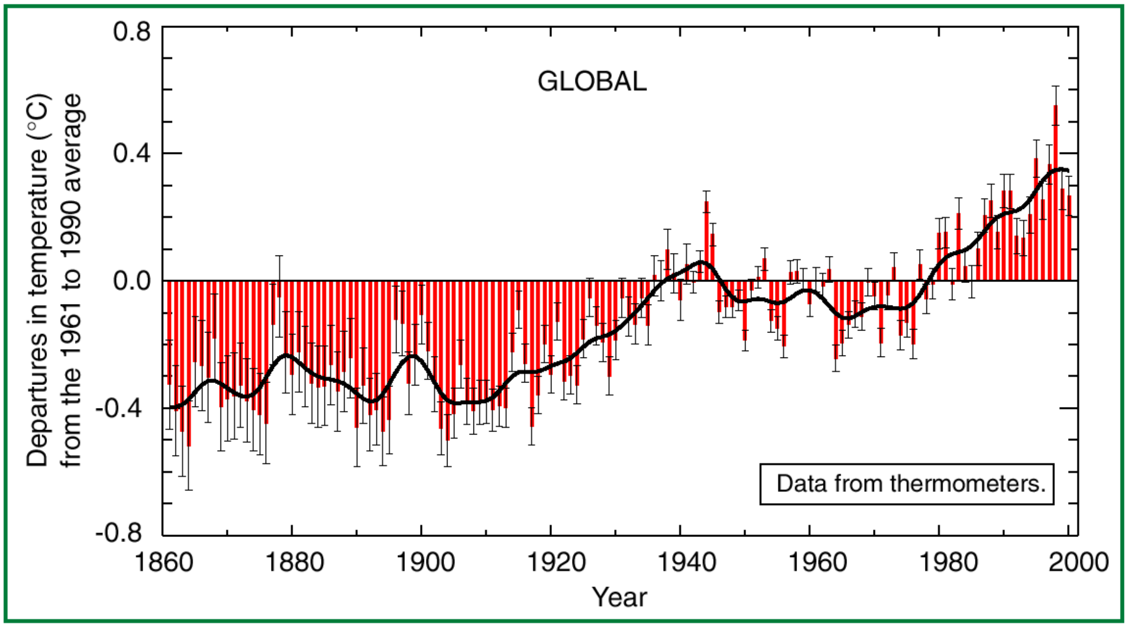


Figure 1. Combined global temperature anomalies 1861 to 2000 [Ref [2], SPM, Fig 2, pg 3].

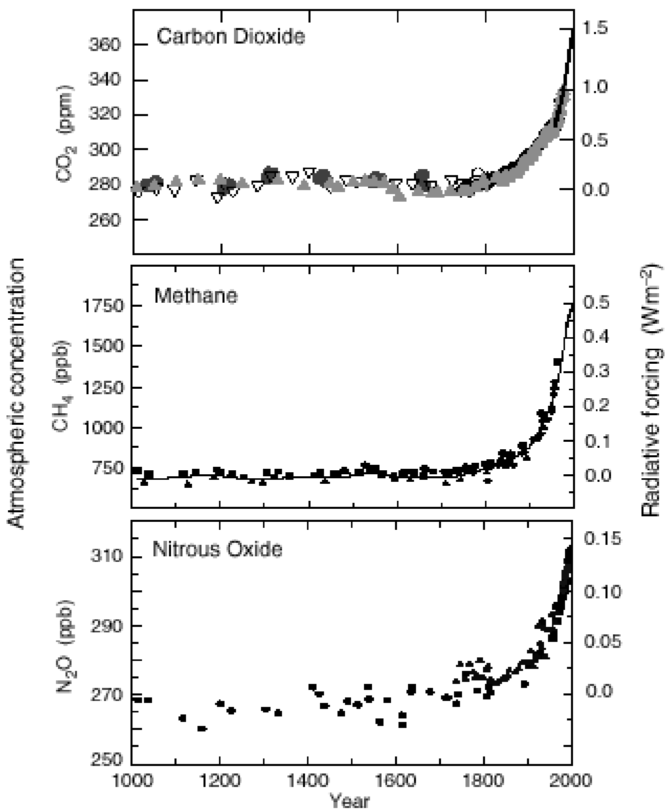


Figure 2. Atmospheric concentration of greenhouse gases over the past 1000 years. The estimated radiative forcing function is given on the right-hand scale. Radiative forcing in this context is the change in net energy flow (in W/m^2) to the Earth and atmosphere caused by the presence of a certain amount of CO_2, methane, or nitrous oxide. Thus CO_2 has the largest effect of these three gases. (Ref [2], TS, pg. 36, Fig. 8)

Figure 1 (above) shows the global surface temperature variation from 1861 to 2000 in the latest report from the IPCC [2]. Figure 2 shows the concentration of greenhouse gases over the last 1000 years. The "radiative forcing" on the right-hand axis indicates the relative effects of the various gas concentrations.

According to Ref [2], enough is now known to say that CO_2 has caused the warming over the last 50 years:

> In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations ([2], SPM, pg 10).

In ref. [2], “likely” has a technical meaning of 66% to 90% chance of being true. It is interesting to note that there was a long, slightly cooling period from 1940 to 1980 and a warming trend from about 1910 to 1940 as steep as the one from 1980 to present. At the same time, CO_2 emissions and CO_2 atmospheric concentrations (and concentrations of other greenhouse gases) were steadily increasing, as was deforestation. The explanations for these different behaviors are complex and are related to atmospheric and ocean currents. Therefore there is not an immediately obvious high correlation between global warming and atmospheric CO_2 concentration over the last 50 years.

The same report notes

> Emissions of CO_2 due to fossil fuel burning are virtually certain [>99%] to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century ([2], SPM, pg 12).

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization and the UN Environmental Programme as a world-wide collaboration “to assess the available scientific, technical, and socioeconomic information in the field of climate change [1].

The Framework Convention on Climate Change was adopted by the UN in 1992 with the objective to “achieve…stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” Meetings in 1995-6 produced an agreement to formulate a plan to reduce CO_2 emissions. The Kyoto meeting in 1997 led to the Kyoto Protocol, which was a CO_2 reduction plan for the industrialized world that had the United States reducing CO_2 emissions to a level 7% below its 1990 levels by the year 2010 [1].

A few months before the 1997 Kyoto meeting, a “sense of the Senate” resolution was introduced by Senators Byrd (D) and Hagel (R) saying that the US should not accede to any agreement limiting CO_2 that would harm the US economy and that would not limit the CO_2 production of developing countries; this resolution passed 95-0 [8]. In July 2000 the Senate passed an Interior Appropriations bill which included a ban on using any of the money appropriated to implement the Kyoto Protocols [9]. The Kyoto Protocol itself was never submitted to the Senate for ratification, and recently it was explicitly disavowed by President Bush.

Global Temperature Measurements

In order to discern long-term climate change, it is necessary to determine annual or longer-term average temperatures over the entire globe to an accuracy of a few tenths of a degree

Celsius. The difficulty of this task can be appreciated when one considers the considerable spatial and temporal variability of the Earth's climate. At most locations on the Earth's surface, temperatures vary daily by 10-20 ºC, seasonally by 40 ºC, spatially (from pole to equator) by 40 ºC. If one considers the entire depth of the atmosphere, additional vertical variations of 70˚ C must also be considered. While direct determination of the Earth's temperatures have been available for the past 200 years, it is only recently that these measurements have begun to approach the quality needed to accurately assess trends.

Over the past 40 years, three approaches probably constitute the most accurate methods for assessing global atmospheric mean temperatures. Since 1979, "microwave sounding units" (MSU) aboard a series of low-earth orbiting satellites have measured temperature-dependent infrared emissions over large portions of the atmosphere ([10]; [2], pp. 27ff; [11]). Balloon-borne instruments have been launched twice daily over the entire globe since 1960 [12]. Lastly, surface temperature measurements themselves have improved in both spatial coverage and measurement quality.

Fig. 3 shows IPCC seasonal estimates of global annual average measured by the three techniques described above (data digitized from [2], pp 27ff, Fig.4). Surface and balloon measurements were made throughout this 40-year period, while satellite-derived measurements have only been available since 1979.

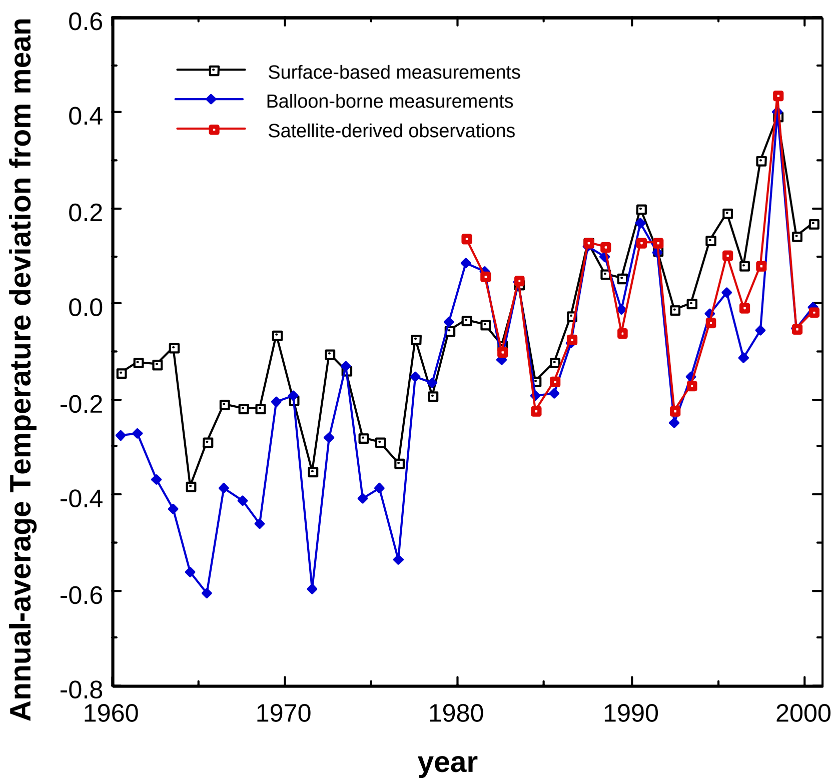


Fig. 3. Annual and globally-averaged temperatures during the past 40 years according to three measurement technologies.

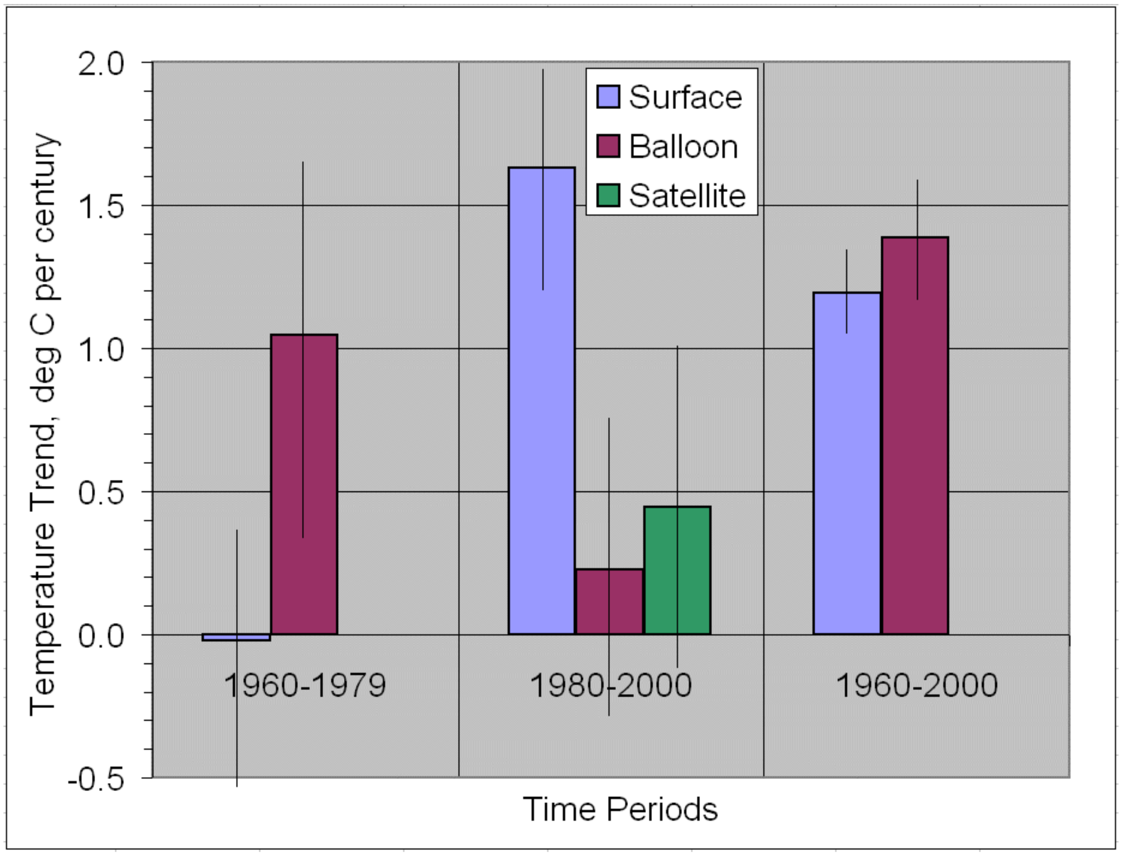


Fig. 4. Trends in annual global-average temperatures derived from Fig. 3 during selected time periods during past 40 years.

Warming rates shown in Fig. 4 were calculated from a linear least-squares regression through the data in Fig. 3 for different time periods. $\pm 1\sigma$ uncertainties are shown for the fitted slopes ([13], Ch.3). Over the full 40 years, the surface-derived temperature trends agree with the balloon data, showing a warming of approximately 1.3 ˚C per century. When trends are calculated from smaller 20-year intervals, some variability and inconsistencies appear. According to balloon measurements, most of the warming occurred from 1960 to 1979. From 1980-2000, the balloon data show much less warming. In contrast, surface temperatures show the reverse: almost no temperature change from 1960-1979, and considerable warming from 1980-2000. While satellite measurements are only available from 1980-present, these agree with the balloon results, showing little warming. However, the overlap or near overlap of various uncertainties indicate that one should be cautious in attaching too much significance to these differences.

These measurements are complex and a myriad of corrections are needed to obtain final results from the raw data. Surface-based measurements are made, as noted above, in enormously varied locations and conditions. For example, one of the important effects that must be taken into account to analyze these data is the "urban heat island" effect which requires a correction because cities are warmer than the surrounding countryside ([2], Box 2.1, pg. 106). The balloon measurements are made only twice daily, and instrumentation and measurement protocols have changed over the measurement record. The MSU data comes from different satellites whose instruments have different sensitivities and these must be carefully calibrated to keep their data consistent [10, 11].

All measurements show large year-to-year variations of 0.1-0.2 ºC, changes that are considerably greater than the averaged changes in mean temperature over the observation period. With such large variability over this short period of time, it is difficult to definitively assess globally-averaged temperature trends.

How Much CO_2 Control?

Despite uncertainty in the magnitude of CO_2 climate effects, CO_2 is a greenhouse gas, its level is rising, and, in principle, it is desirable to control CO_2 emissions and atmospheric concentration. The world is using an increasing amount of energy and, absent major technological and political breakthroughs, the greatest part of this energy will be produced by burning fossil fuels. Thus the questions of control are how much, where and when.

Figure 5 below shows the global C cycle including C reservoirs and annual average CO_2 fluxes in the decade 1980-89 [14-16]. Time constants for equilibration are decades to hundreds of years. The average annual global CO_2 budget for 1980-89 was approximately as follows: anthropogenic CO_2 emissions, 5.5 GtC; CO_2 atmospheric increase, 3.3 GtC; and annual global CO_2 molar concentration increase, 1.5 ppm ([14], Tables 1-2, pp38-39). (GtC = gigatons C = 10^9 tons of C.)

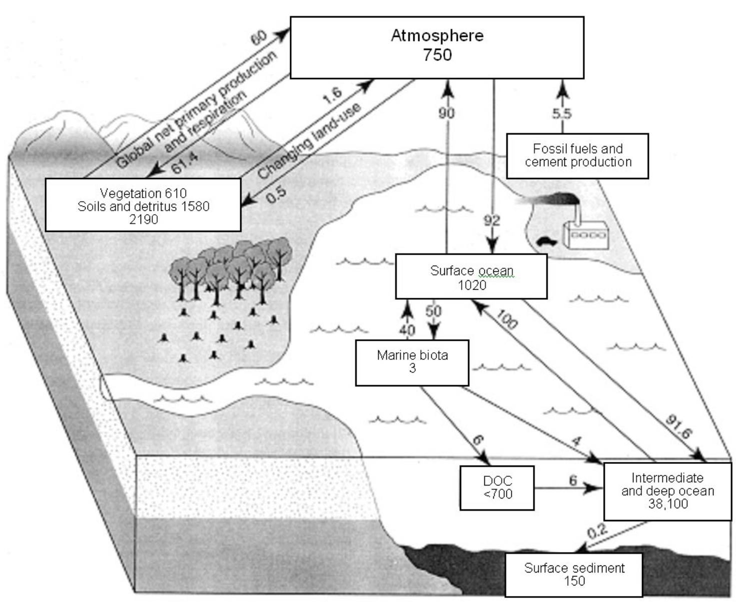


Figure 5. Global C cycle showing C fluxes and C reservoirs. The anthropogenic emissions (fossil fuel burning and cement production) have generated an increasing concentration of CO_2 in the atmosphere. Reservoir figures are in GtC and flux values are in GtC/yr averaged over the decade 1980-1989 ([14-16]).

Figure 6 shows known and projected carbon emission by region of the world from 1990 to 2020. The USA in 1990 produced approximately 1.47 GtC [3]. The greatest increase in energy use and consequent C production is in the developing countries, mainly in Asia.

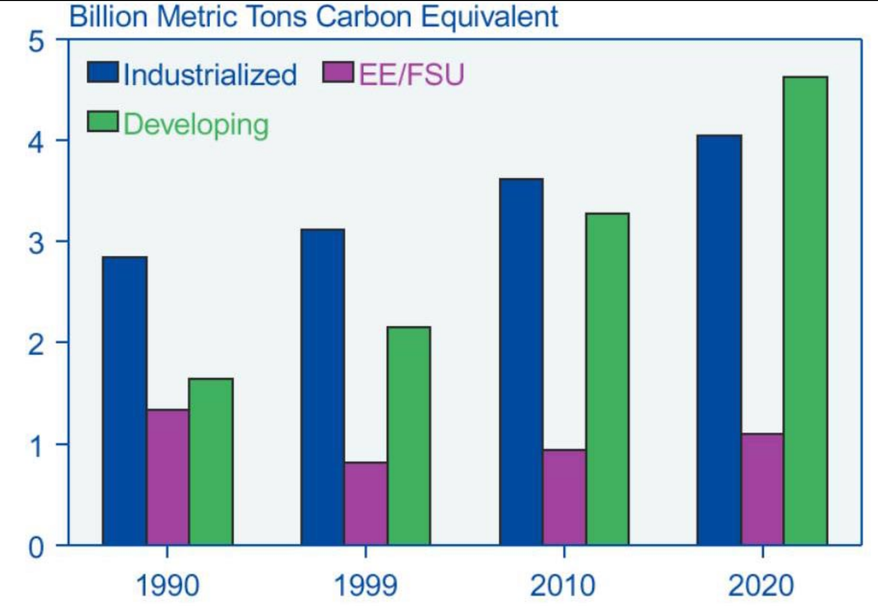


Figure 6. World C emissions by world region, 1990-2020 [Ref [3], Fig. 20]. (EE/FSU stands for Eastern Europe and the Former Soviet Union.) Note the rapid growth of C emissions of the developing countries—this is mainly Asia. Sources: **1990 and 1999**: EIA, *International Energy Annual 1999*, DOE/EIA-0219 (99) (Washington, DC, January 2001). **Projections**: EIA, World Energy Projection System (2001).

Figure 7 shows world C emissions with and without the Kyoto reductions [3]. "Annex 1" includes the industrialized countries and "Non-Annex 1" are the developing countries. The developing countries are not required to reduce their C output and, as is evident from Figure 6, most of the growth of C emissions occurs in developing countries. It is important to note from Fig. 7 that C emissions would not be strongly affected by Kyoto. In 2010 the total reduction is from 7.8 to 7.3 GtC (6.5% decrease) and 9.8 to 8.7 GtC (11.3%) in 2020.

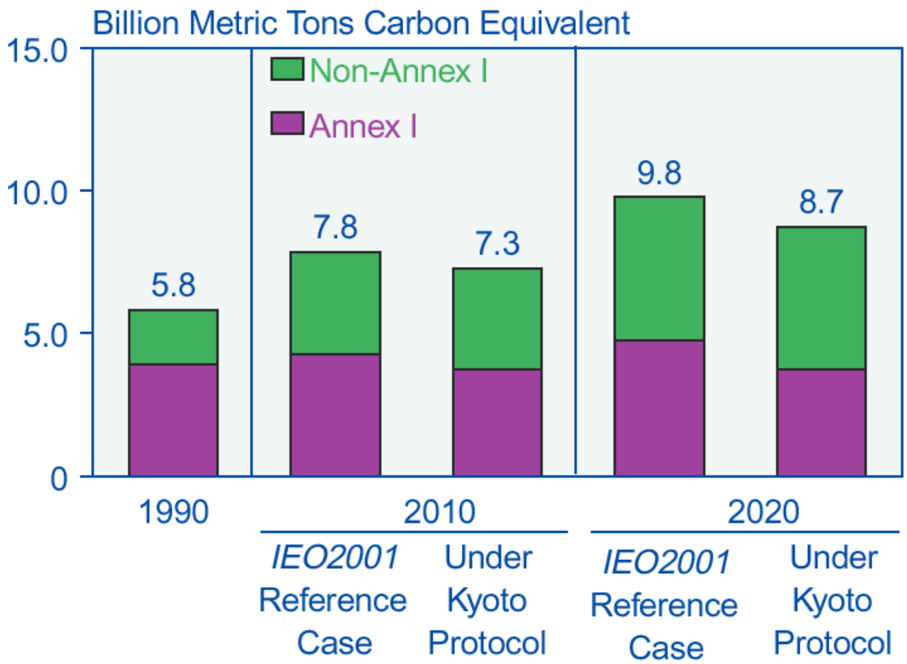


Figure 7. World C emissions in the IEO2001 Reference Case and under the Kyoto Protocol, 2010 and 2020 ([3], Fig 11). "Annex 1" is a list of the developed countries and "Non-Annex 1" are the developing countries. The developing countries do not have to limit their C production. Note that the total C emissions are not that different when the Kyoto Protocols are in place. The C emissions are decreased from 7.8 to 7.3 (6.5%) in 2010 and 9.8 to 8.7 (11.3%) in 2020. Sources: **1990**: EIA, *International Energy Annual 1999*, DOE/EIA-0219 (99) (Washington, DC, January 2001). **Projections**: EIA, World Energy Projection System (2001).

Figure 8 shows the energy and C produced by various fuels [3]. Coal is essentially pure C and produces the greatest amount of C per unit energy generated when it burns. Natural gas (CH_4) produces the least C emission and will be a major factor in lowering C energy production. The projections show the energy output from gas and coal about equal now, with gas energy outstripping coal energy in the future.

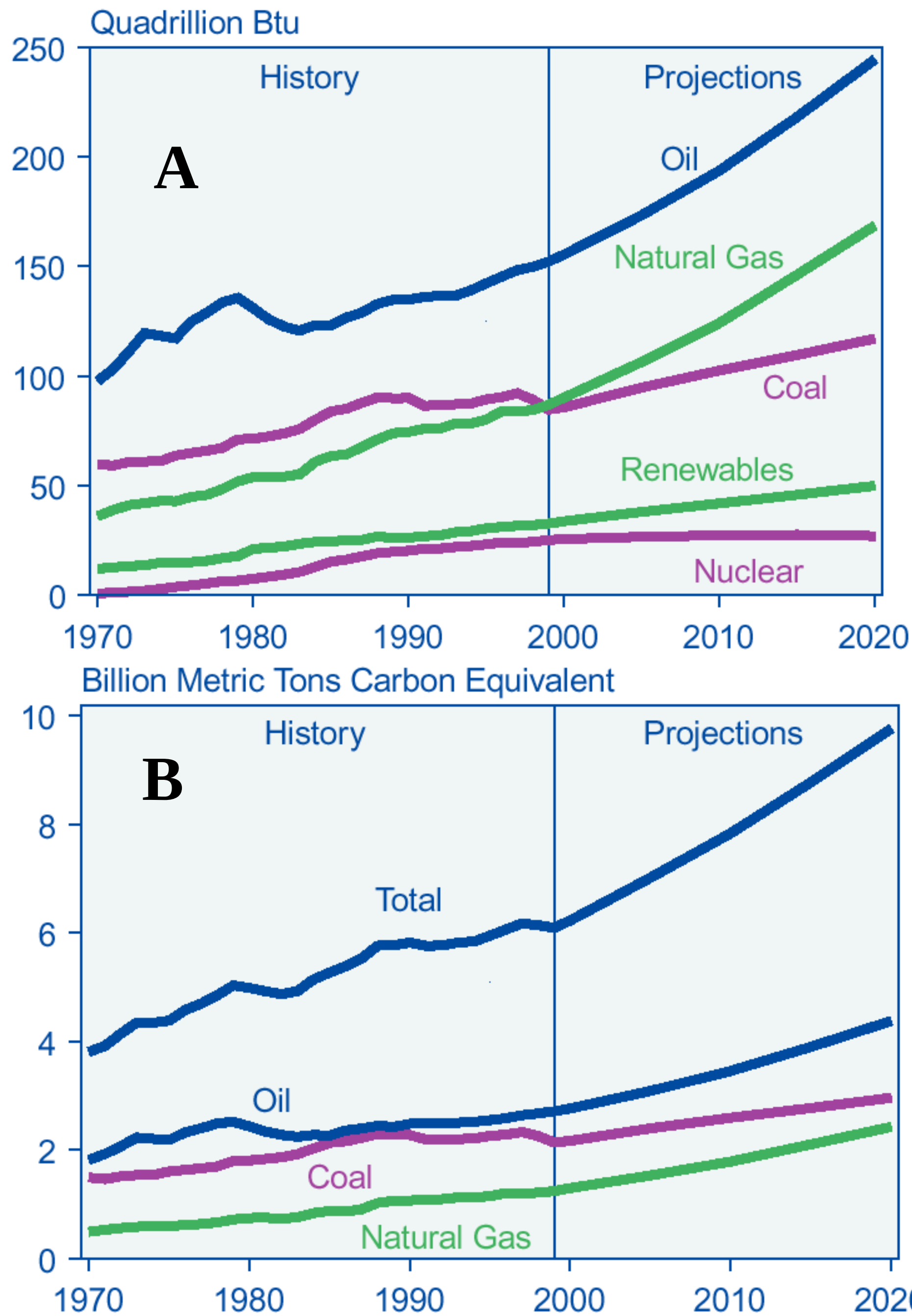


Figure 8. World energy consumption (A) and C production (B) for various fuels ([3], Figs 17, 19). Gas is obviously most efficient in terms of C emission per unit energy produced. Sources: **History**: EIA, Office of Energy Markets and End Use, International Statistics Database and *International Energy Annual 1999*, DOE/EIA-0219 (99) (Washington, DC, January 2001). **Projections**: EIA, World Energy Projection System (2001).

One important piece of data is the energy use per capita and consequent C emissions in various regions of the world as shown in Figure 9 [3]. Per capita C emission in North America (US and Canada) is almost 9 times that of China and about twice that in Western Europe. By 2020, if the world continues on its present course, per capita C emission will rise slightly in North America and more than double in China, but China will still be far behind. As discussed above, the total energy use and C production of developing countries by that time will outstrip that of the industrialized world. However, because of the per capita energy and C production discrepancies, it is not clear that the industrialized world will have the moral standing to tell China and other developing countries to slow down their development. Thus the potential for C emission is enormous, even assuming population stabilization.

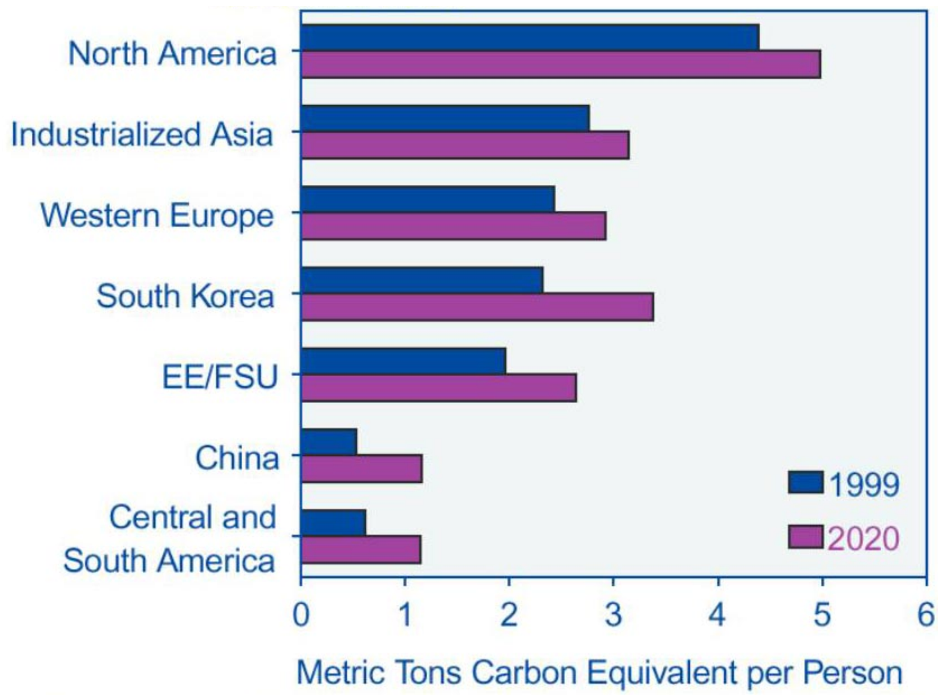


Figure 9. Per capita annual C emissions in selected regions and countries, 1999 and 2020 ([3], Fig. 95). Sources: **1999**: EIA, *International Energy Annual 1999*, DOE/EIA-0219 (99) (Washington, DC, January 2001). **Projections**: EIA, World Energy Projection System (2001).

Given the inequalities in Figure 9, it is difficult to see how even a substantial cutback by industrialized countries would impress the developing world so that the latter would limit their own development. C-reducing technologies from the developed world could be transferred to the developing world under appropriate circumstances. However, combined-cycle gas-steam electrical generation may not be very useful in countries that rely heavily on coal for electric power production and do not have a readily available source of gas.

It is important to understand the consequences of C emissions on atmospheric CO_2 concentrations and global temperature. It has been suggested that it would be desirable to stabilize CO_2 levels at about 550 ppm, or twice the pre-industrial value shown in Figure 2 above. Recent climate modeling (Fig 10) has examined a "business-as-usual" case where the CO_2 level in 2100 is 710 ppm and a stabilization scenario where CO_2 concentration is about 540 ppm in 2100 and levels out at 550 ppm in 2150. The difference in temperature at the end of the 21st century for these two courses is less than 0.5° C [17, 18]. Under either C reduction scenario ("business as usual" or very large C emission reductions), worldwide temperatures are projected to be about 2º C warmer than pre-industrial global averages.

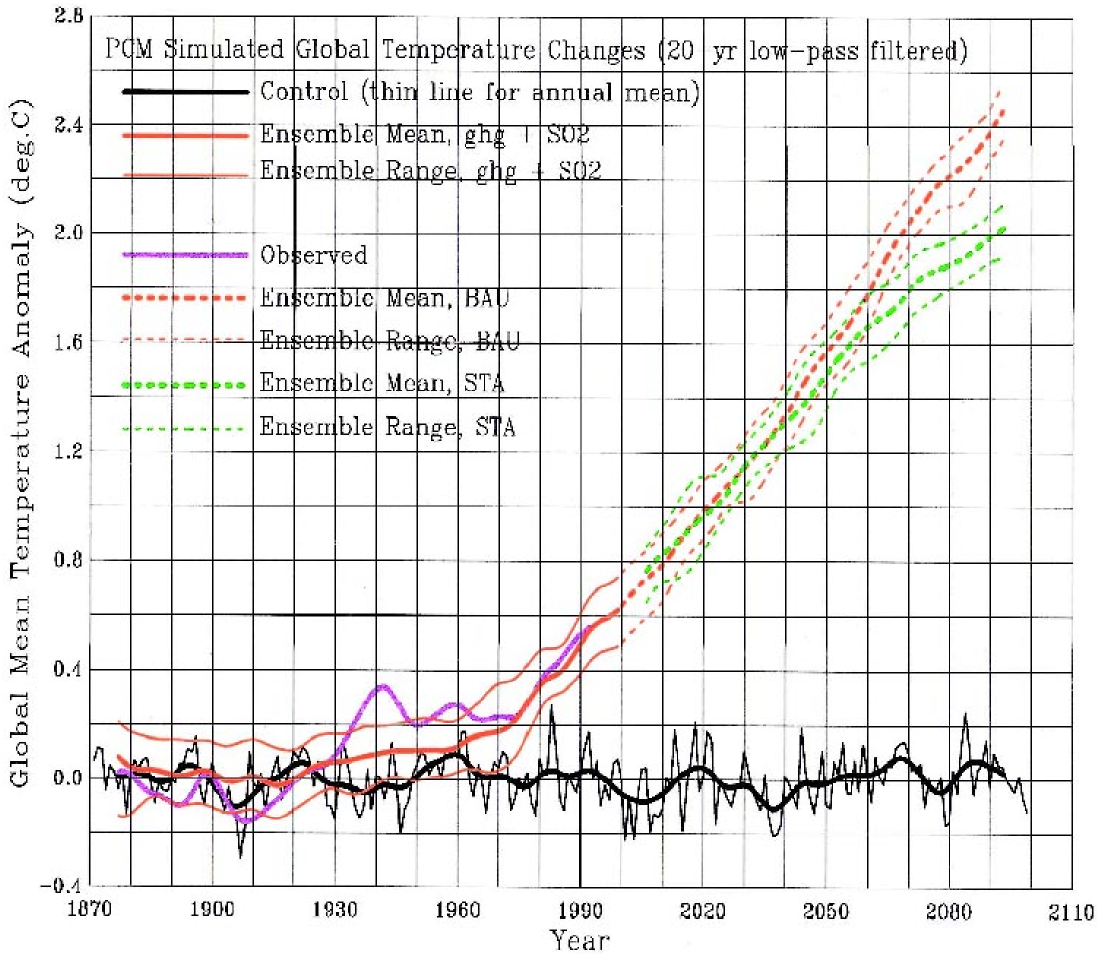


Figure 10. Historic and modeled global temperatures from 1870 to 2100. The BAU (business-as-usual) case (red lines) corresponds to a CO_2 concentration in 2100 of about 710 ppm. The "stabilized" case (green lines) corresponds to implementing controls aiming to stabilize CO2 levels at 550 ppm in 2150. At 2100 the CO_2 levels are about 2140 ppm. (The black curves are from a control run.) [17]

Equity, Contraction and Convergence

The world population was 6.1 billion in 2000 [19]. If we divide the total C emissions in 1990 (5.8 GtC, Fig. 7) by this figure we get 0.94 tC per capita per year. Thus, if the 1990 global C emissions were spread uniformly over the globe, the world *average* per capita C emissions in 2010 and 2020 would be about what people in China and South America are producing now (Fig. 9). There is little room for increase for the Chinese or South Americans, and people in the USA would have to cut back their C emission by a factor of five from present levels in order to achieve the required world average.

The idea that the developing world might be willing to consider limiting their C emissions if, in the long run, everyone will have the opportunity to use approximately the same amount of energy is the issue of “equity.” The Global Commons Institute of the UK advocates this idea in their plan of “Contraction and Convergence,” and their graphs show the US reducing its output by a factor of 10 or more to achieve equity [20]. The basic idea is that the goal is to equalize C output, and the pace of change would be internationally negotiated. While inequality exists, C emission rights could be bought, sold and traded. In general this would result in a flow of money from rich to poor countries.

Exactly how the C reduction would occur is not specified, but rich countries would be highly motivated to reduce C emission through technology. It must be noted that this kind of reduction is at least an order of magnitude greater than the Kyoto figures, so correspondingly more ambitious and longer-lasting steps must be taken. This could include, for example: a massive increase in electric power production by non-burning methods, i.e., wind power, hydro power, solar power or nuclear power; a widespread use of H fuel; a highly successful way of capturing C output and putting it back into the ground, trees, water, etc (C sequestering).

Figure 11 shows a “C&C” scenario that gets everybody in synch by 2030 [20]. It is hard to envision the world accomplishing such a radical change by this time, but it may be desirable to keep this goal in mind, even if it is carried out over a longer period.

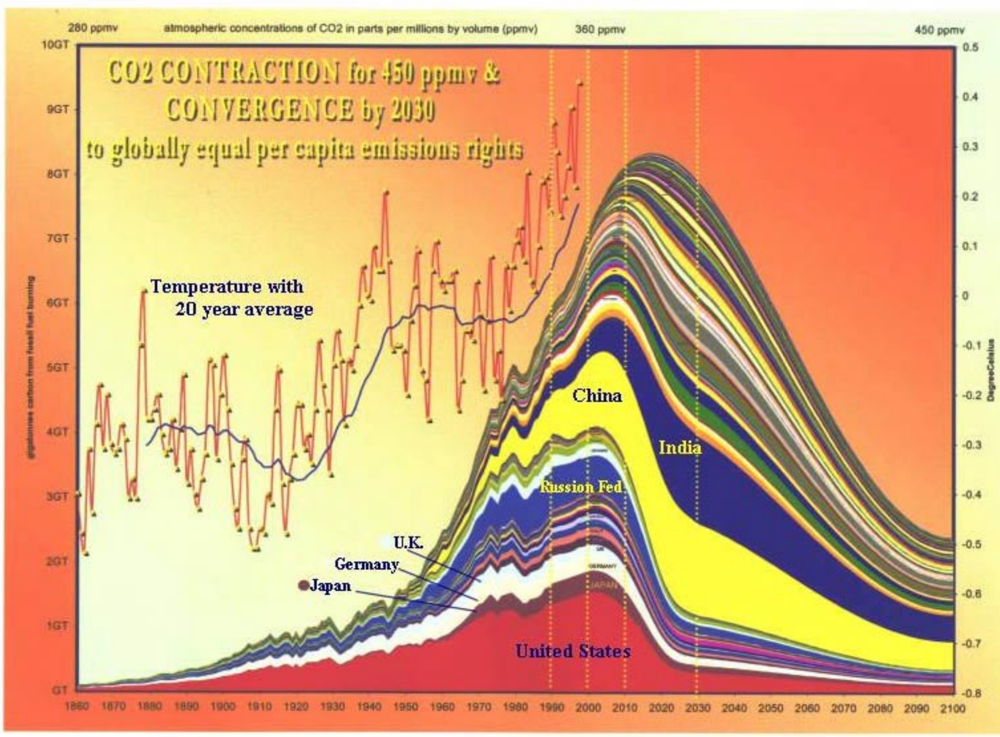


Figure 11. “Contraction and Convergence” scenario ([20], pg 32ff).

C Reduction Scenarios Related to Kyoto [1]

The DOE EIA in reference [1] has a series of C reduction scenarios, shown in Fig. 12 below, spaced between “reference,” in which case 2010 USA C emissions are 34% above the 1990 level, to “1990-7%,” which is the Kyoto Protocol goal. This is a useful exercise in which the EIA attempts to spell out a detailed path to achieve each of these objectives along with the consequences of these approaches. Serious reductions begin in about 2004, continue to 2008 and then the C production levels are constant [1]. Which reductions occur are a result of the EIA economic model [1].

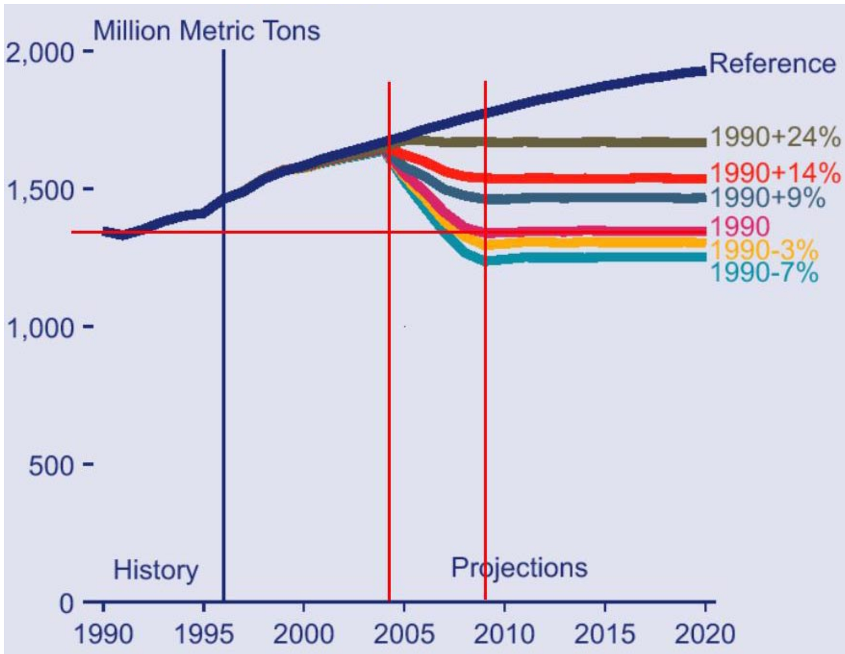


Figure 12. Projections of C emissions, 1990-2020 ([1], Fig. ES1].

Table A1 (Appendix) shows various parameters associated with different C reduction scenarios [1]. The costs are imposed as carbon taxes or permits. Revenues collected in carbon taxes would be used for personal income tax rebates. The column marked “Reference” is the scenario where nothing is changed, i.e., there is a 34% C emission increase in 2010 as shown in Figure 8 above. We calculate a current nominal C cost at about $450/tonne assuming a cost of $1/US gallon of fuel (mass ~ 2.4 kg). 1 kg of gasoline produces about 48 MJ or 45,000 BTU of energy [21].

Appendix Table A2 shows some consequences of C reduction. As higher C costs are imposed, fuel prices increase and total energy use decreases. However, it is interesting to note that gasoline prices rise to only $1.91 per gallon, a figure that some parts of the American Midwest have already experienced, in the case where the full Kyoto C reduction is achieved,. The average electricity cost goes up to 11.0 cents per kWh. However, the cost in many states is already at that level or higher [22]. The GDP is predicted to go from $6.93 trillion in 1990 to $9.43 trillion in 2010 if we do not moderate C emissions or to $9.03 trillion if we do enough to achieve Kyoto, a difference of only 4%.

Other views of the C costs necessary to change behavior and drive C emission lower are found in references [5] and [23]. These sources try to factor in a fast pace of innovation which the EIA says is unrealistic [24]. However, the resulting GDP differences in the different models are a small fraction of the total GDP.

CO_2 Reduction: Energy Efficiency and Energy Conservation

We will now briefly discuss possible strategies of energy efficiency as an approach to reducing CO_2 emissions. It is useful to note the distinction between energy efficiency and energy conservation.

> Energy efficiency means improving equipment and systems to get the same output (e.g., miles traveled or widgets produced) but with less energy input. Energy conservation means reducing energy use, and at times may mean reducing the services received. Examples of energy conservation include changing thermostat settings, reducing lighting levels, and driving less. To the extent energy conservation eliminates waste it is generally desirable. For example, many commercial buildings are excessively lit and over air-conditioned, wasting large amounts of energy without providing any useful service [25].

Reducing C using primarily energy-efficient means might be relatively painless, although energy-efficient does not necessarily imply cost-effectiveness. However, reducing energy used does save money, and these savings can offset capital investment over time.

The value of particular energy efficiency or conservation strategies is often stated in terms of an impressive amount of energy, money, CO_2 etc. saved—this can be millions or billions of joules, dollars or kilograms because of the large numbers involved—while neglecting to point out that the saving is a negligible fraction of the quantity of interest. For our purposes here, we will examine these quantities in terms of what fraction of the Kyoto goals are achieved.

Electric Power C Emission Reduction

Figure 13 below shows C emission reduction by end-use sector for three C reduction levels [1]. Reductions from electricity generation account for most of the total C reductions, including 70% in the 1990-3% case [1].

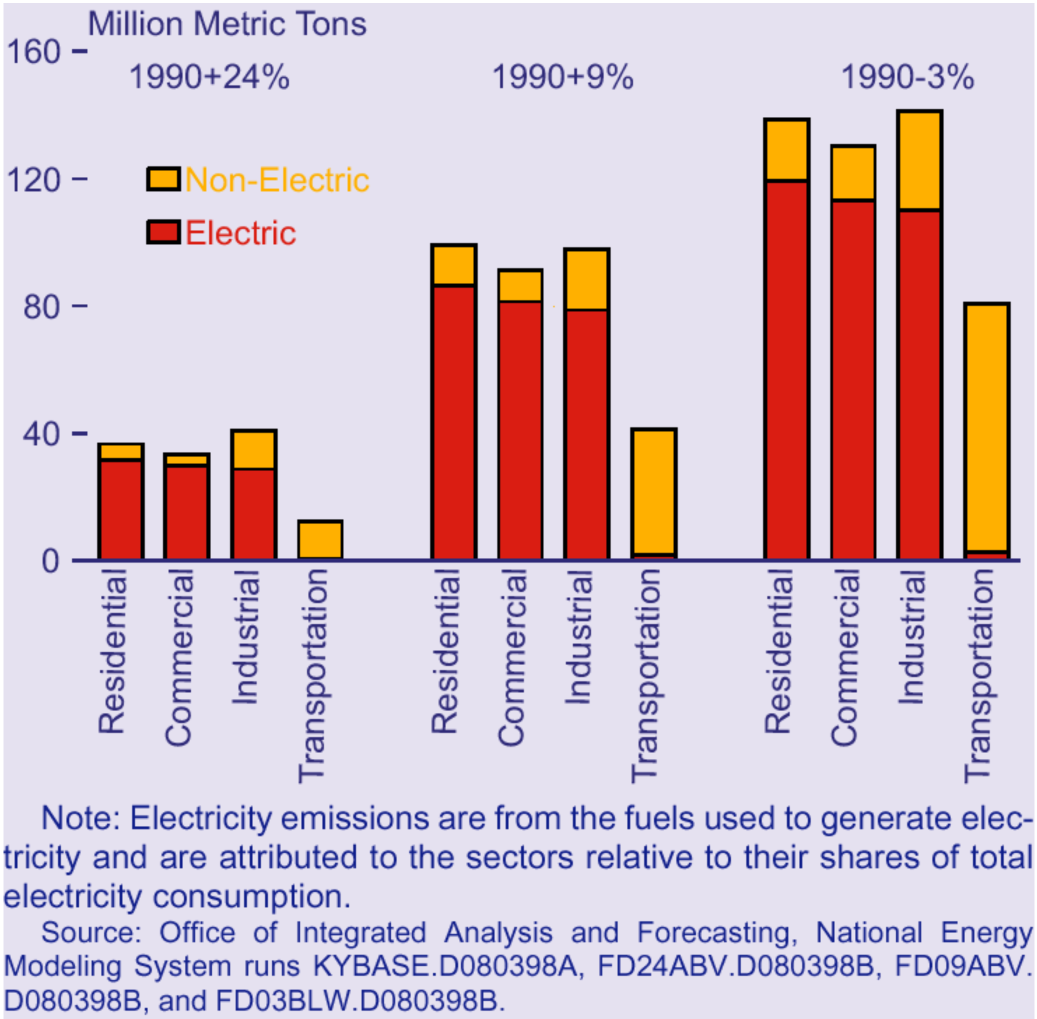


Figure 13. Projected C emission reductions for different C reduction scenarios; electric and non-electric components (Ref [1], Fig 16).

Present and future status of various electricity-generating technologies are outlined in Table A3 [5]. The relevant point is that most fossil fuel electric generation is presently done by burning coal that produces 260 gC (grams of C) per kWh of electricity. Changing to gas turbine reduces this figure to 170 gC/kWh, and going to gas/steam combined cycle reduces the output further to 100 gC/kWh. Combined-cycle plant installation is rapidly ramping up.

Figure 14 shows the C emission reduction for the 1990–3% scenario for the electricity supply sector. In this case the electric power sector would reduce its emissions by 54%. This would be accomplished mainly by changing from coal to natural gas as a fuel

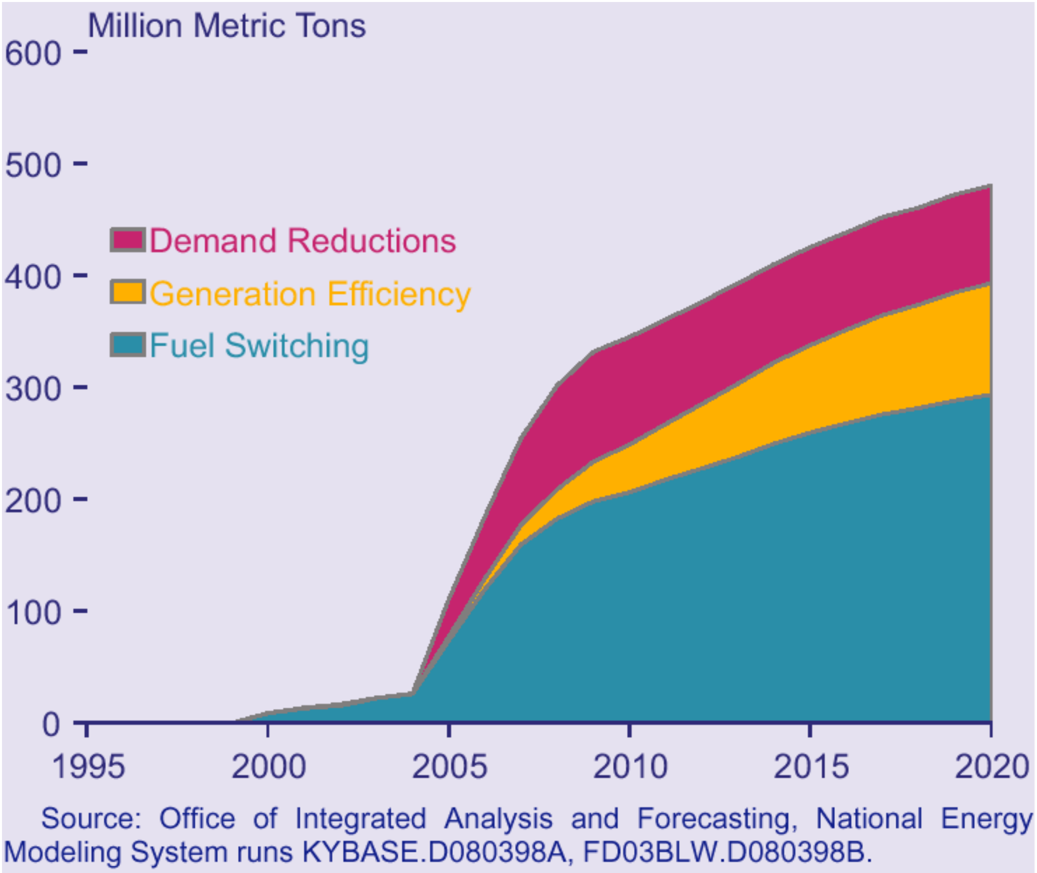


Figure 14. C reductions from electricity supply, 1990-3% case ([1], Figure ES5).

Industrial Demand[1]

The industrial sector accounted for over 1/3 of US energy consumption and 1/3 of C emissions in 1996. From 1980 to 1996, industrial output rose faster than energy consumption and energy intensity (Btu/dollar output) fell 20%. In 1995, energy costs were only 2.3% of annual manufacturing outlays. In general, energy prices and technology innovations do not have a large effect on industrial energy use. Most of the C savings in the industrial sector would be attributable to more efficient generation of electricity that industry uses [1].

Industrial production would be decreased in the C reduction scenarios. Production would be 1%, 3% and 6% lower for the cases of 1990+24%, 1990+9% and 1990-3% respectively. Energy costs would be 22% higher, 55% higher and 95% higher for these three scenarios.

One technology use that could produce considerable C reduction is cogeneration systems [1]. These are the use, for example, of gas turbines for electricity generation plus the use of gas turbine waste heat for steam production and subsequent building space heating. Such systems are nearly twice as efficient per unit fuel as electricity generation alone. Thus a cogeneration system could be located either at a large industrial site or an area of concentrated activity such as a city center [1, 26].

Commercial Demand[1]

The commercial sector consists of businesses, restaurants and hospitals as well as schools and other buildings used for non-private use. The main energy use of the commercial sector is lighting and HVAC. In 1996 the commercial sector accounted for 11% of the energy and 16% of C emission and is the smallest of the demand sectors [1]. Commercial buildings last a long time, so changes are slow as is the implementation of innovation; over half the commercial buildings in the US were built before 1970. For higher C reduction scenarios with higher C prices, consumers (i.e. building and business owners) would purchase more efficient HVAC, including heat pumps, and more efficient lighting technologies. Again, most of the C savings would be attributable to C savings in electricity generation [1]. Cogeneration could also play a significant role [1, 26, 27].

Transportation Demand [1]

The largest C emissions for transportation come directly from fuel combustion. In 1996 this sector accounted for 33% of all C emissions and 78% of C emissions from petroleum use. Transportation C emissions are expected to grow at an average annual rate of 1.9% to 2010 compared to 1.4% for the commercial sector and 1.2% for both residential and industrial sectors [1].

The transportation sector is the only one that does not reach 1990 levels with any of the EIA C reduction scenarios [1]. The increases go from 49% (no C reduction scenario) to 30% increase for the 1990-3% scenario [1].

Automotive Efficiency

With the renewed concern about energy supplies, particularly petroleum, the efficiency of automobiles and light trucks (including SUVs) is under intense scrutiny [28]. Although Corporate Average Fuel Economy (CAFE) requirements (27.5 mpg for new passenger cars, and 20.7 mpg for new light-duty trucks) have remained static for the past decade, there is sentiment for increasing new vehicle mileage standards, especially for light trucks. Because of the immense popularity of sport utility vehicles and pickup trucks (50% of new sales), the fleet average gas mileage of new vehicles has decreased in recent years [29].

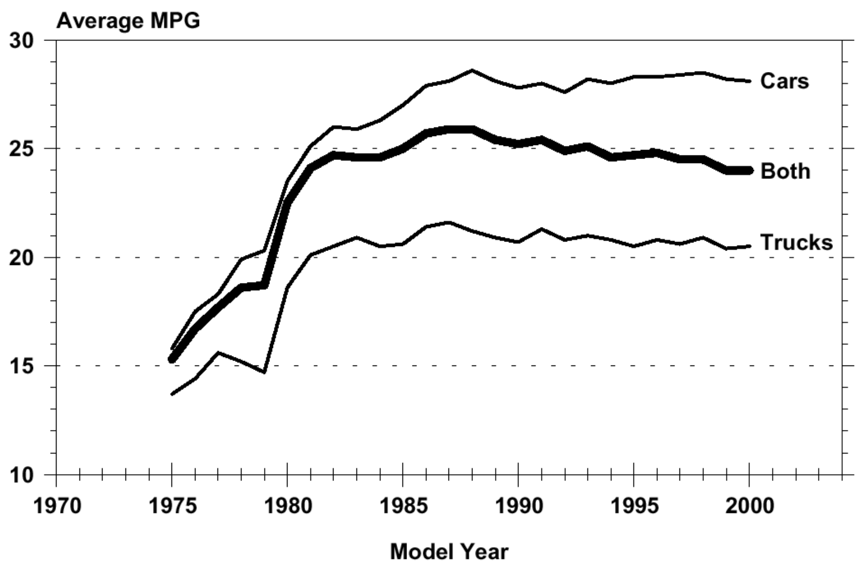


Figure 15. Vehicle fuel economy by model year [29].

Concerns about global warming have focused attention on vehicular emission of greenhouse gases (mainly CO_2). The annual carbon emissions from transportation is 473 million metric tons of carbon (MtC), which is 32.0% of the US total. Light-duty vehicles contribute 267 MtC/year of the transportation total [30]. Projections (based on present-day trends) indicate that this will increase to 346 MtC by 2010, principally because vehicle miles traveled (VMT) is expected to rise 25% (from 2301 x 10^9 to 2886 x 10^9). Although new car mileage will improve from 27.9 to an estimated 31.7 mpg and new light trucks from 20.2 to 20.8 mpg, the lower mileage of the large stock of vehicles in the US (215 x 10^6 vehicles), which now averages about 20 mpg, will largely offset these gains. It generally takes more than 10 years to turn over the stock of vehicles.

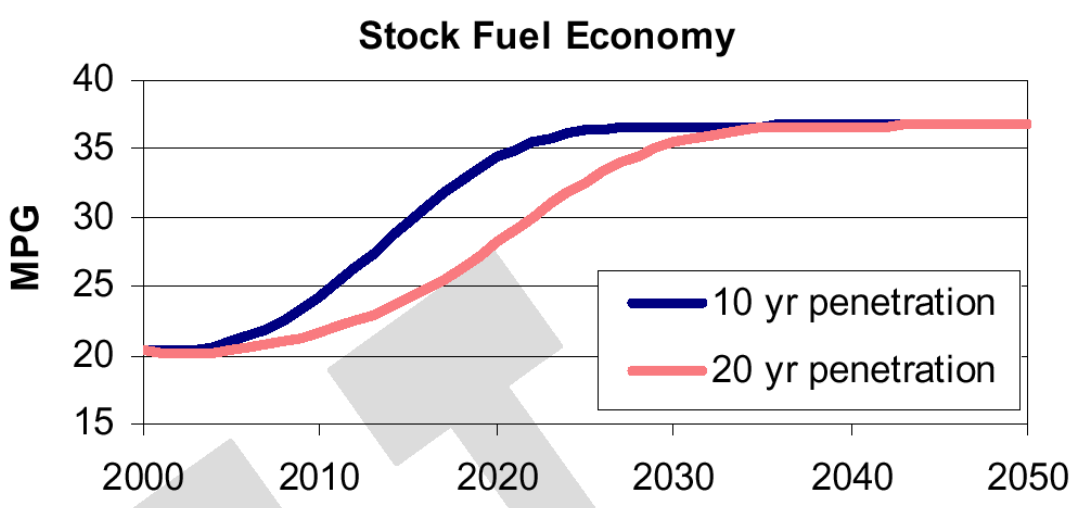


Figure 16. Replacement of existing vehicles with new 37-mpg vehicles [31].

In the near term, the largest increases in gas mileage (with a concomitant reduction in CO_2 emission) for new vehicles will be from hybrid-electric vehicles (HEVs). At present, two

HEVs are on the market in the US: the Toyota Prius and the Honda Insight. These vehicles combine a small gasoline-powered engine and electric motors powered by batteries that are recharged by the engine. No external source of electric power is required, in contrast to all-electric vehicles. The EPA combined city and highway gas mileage for the Prius is 48 mpg and an even higher 64 mpg for the Insight [32]. Most major manufacturers plan to offer hybrid vehicles, including trucks and SUVs, in the next few years. For example, Ford plans to produce a hybrid Escape (small SUV) in 2003. The target mileage is 40 mpg in combined city-highway [33] driving compared to the conventional Escape at approximately 22 mpg.

Electric vehicles are not currently a factor in automotive transportation, except in niche markets. Even though the equivalent mileage (accounting for generation efficiencies and transmission losses) is considerably higher than that of HEVs (e.g., the EV1 was rated over 100 mpg) the limited range (less than 100 miles) diminishes their appeal. Fuel cell vehicles are not thought to be commercially viable in the next ten years, perhaps even twenty [34].

Improvements in gas mileage do not come cheaply. Recouping one's investment in an efficient car or truck (initial incremental cost of several thousand dollars for a 35-mpg vehicle) can take most of its useful life at prevailing gasoline prices. Likewise, the industry/government consortium called Partnership for a New Generation of Vehicles attained the goals of demonstrating an 80-mpg vehicle with the attributes of today's mid-size cars, but did not meet the cost targets.

The National Research Council's 7th annual review of the PNGV program [35] states, "The committee believes that, overall, the PNGV program is an excellent example of how long-range societal goals can be effectively addressed by the efforts of a collaborative, pre-competitive government-industry R&D partnership." But requiring a 2004 production vehicle, as originally planned, was not recommended because the near-term customer affordability requirement could not be met.

The Toyota Prius can be purchased for about $20,000. However, sources on the web say that it probably costs Toyota $30,000 or more to make each Prius, so the present sales are heavily subsidized. Replacing the battery is said to cost $5,000 [36, 37].

DeCicco, An, and Ross reviewed technical options for improving fuel economy, which were subsequently used in a report issued by the Union of Concerned Scientists [38, 39].

Their ***Moderate Package*** entails the following steps:

- Mass reduction: zero net reduction for small cars; 10% for midsize cars; and 20% for minivans, pickups, and SUVs
- Aerodynamic streamlining, reduced tire rolling resistance, and accessory improvements
- High-efficiency, lightweight, low-friction, precision-controlled gasoline engine
- Integrated starter-generator (ISG) with 42 volt (V) system
- Improved transmissions depending on vehicle type

Their ***Advanced Package*** includes the following choices:

- Greater mass reduction: 10% for small cars, 20% for large cars, and 33% for light trucks; we also examine an advanced large sport wagon reflecting a 40% mass reduction for its size
- The same streamlining, tire, and accessory improvements as in the Moderate Package
- Gasoline direct-injection engine (GDI, stoichiometric) with 42 V ISG system
- Advanced transmissions, using efficiency-optimized shift schedules for all vehicles

With these modifications, they estimate a midsize car can obtain 46 mpg and a SUV 40-44 mpg. Note we quote unadjusted composite miles per gallon with 55% city driving and 45% highway driving. Real world mileage is generally lower. To reach higher fuel economy hybrid-electric vehicles have to be introduced. Similarly, AuYeung, Heywood, and Schafer estimated fuel economy benefits versus cost for a typical passenger car (like a Toyota Camry) in 2020 [34].

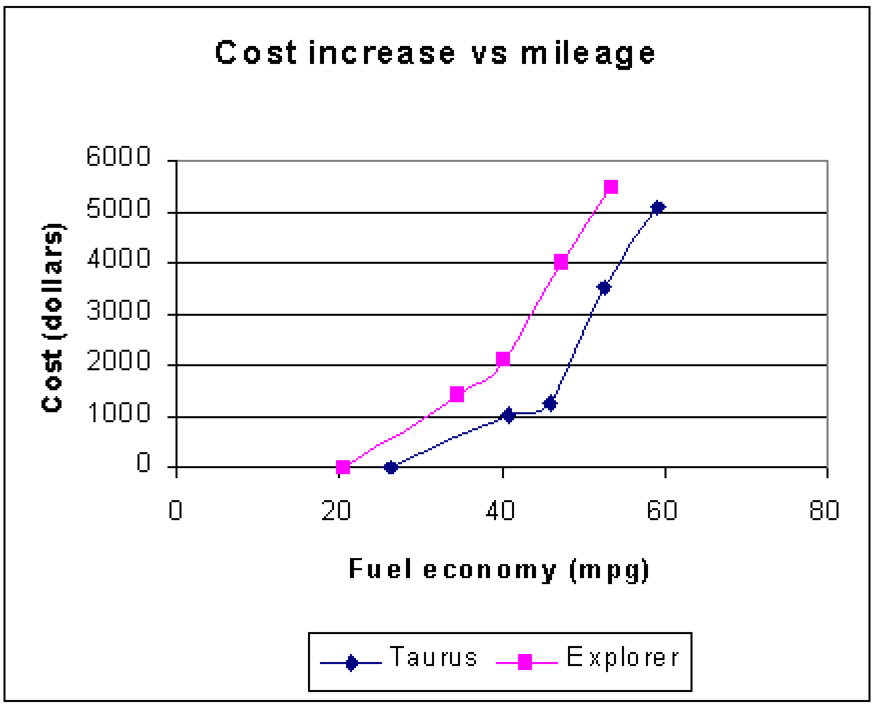


Figure 17. Estimates of cost for fuel economy improvements. Abrupt changes in slope indicate introduction of hybrid-electric technology [34].

To compare the estimated cost for improved gas mileage with the expected benefit, the simplest approach is to calculate the gallons of gasoline consumed over the expected 150,000-mile lifetime of the vehicle, assuming a properly discounted cost per gallon. For example, if we take the price of gasoline to be $1.40/gal and assume that each year for 10 years the vehicle is driven 15,000 miles, then using a 12% discount rate, we find an effective price of $0.886/gal. For both the Taurus and the Explorer, the breakeven point is between the "Advanced Package" and the "Mild Hybrid" estimates by DeCicco *et al* [38].

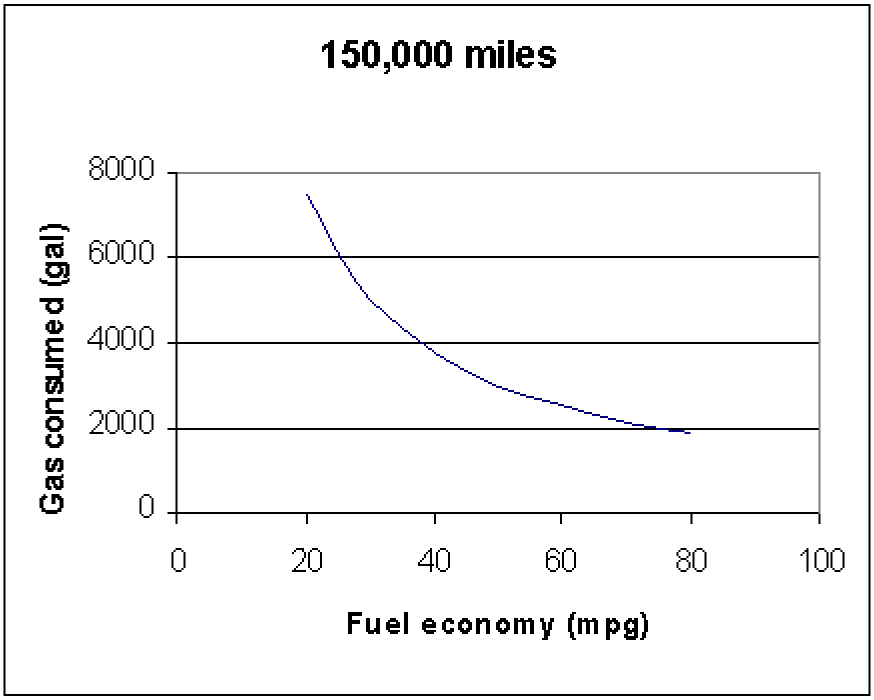


Figure 18. Gallons of gasoline consumed in 150,000 miles versus fuel economy. (Calculated from data in [34].)

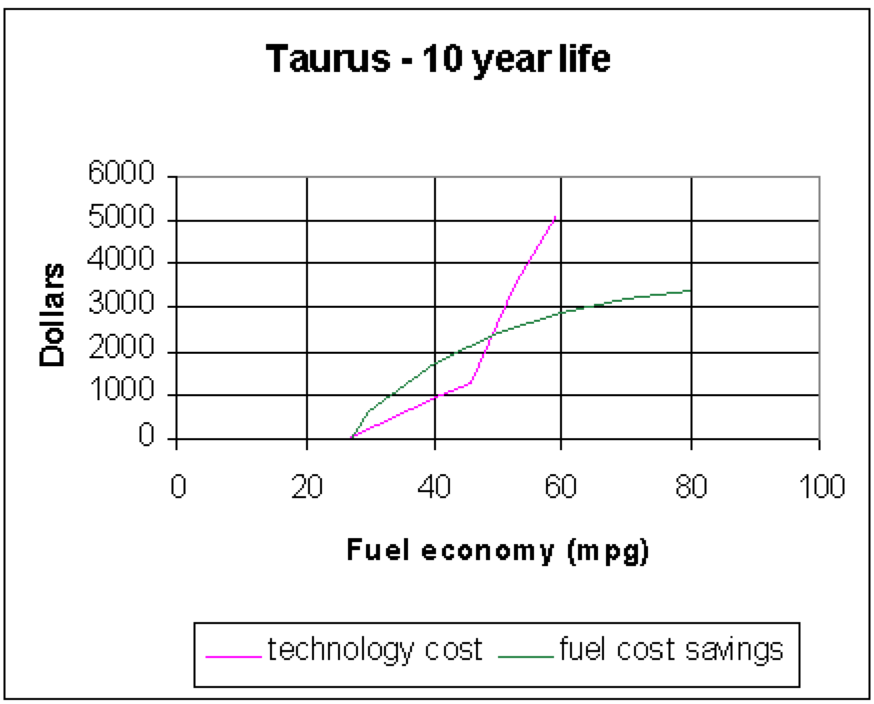


Figure 19. Fuel cost savings and technology cost as a function of gas mileage for a midsize car. (Calculated from data in [34].)

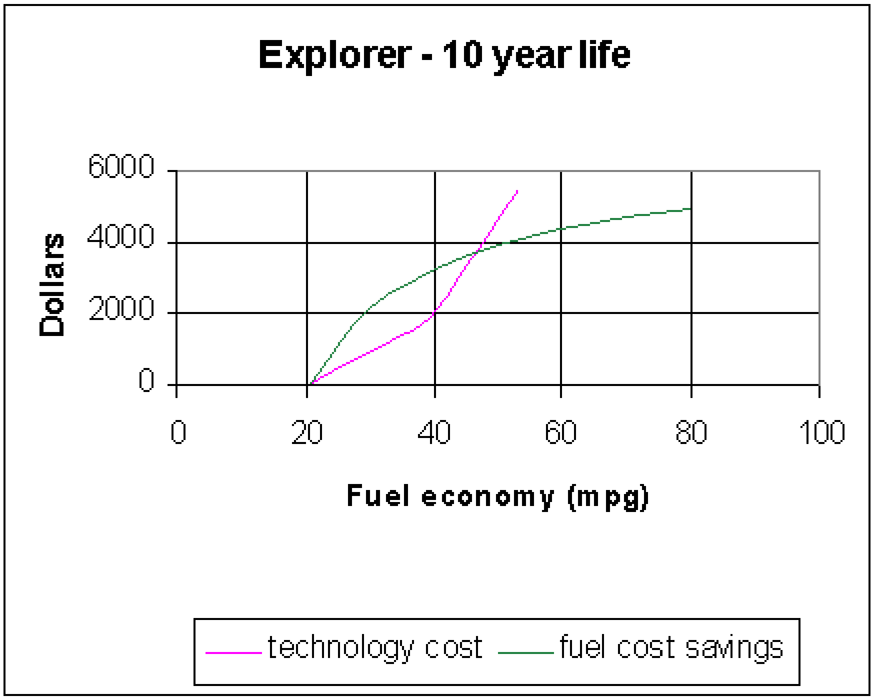


Figure 20. Fuel cost savings and technology cost as a function of gas mileage for a midsize car. (Calculated from data in [34].)

The effective gasoline price may well be low, but the technology cost estimates likewise appear low to veteran automotive industry observers. Using different assumptions, the NRC reached similar conclusions on the breakeven point for a range of vehicles. [34]

TABLE 4-2 Case 1: Break-Even Fuel Economy (FE) Analysis for 14-year Payback (12% Discount Rate)[a]

			Low Cost/High mpg		Average		High Cost/Low mpg	
Cars	Base[b]	Base Adj[c]	FE (mpg, %)	Cost ($)	FE (mpg, %)	Cost ($)	FE (mpg, %)	Cost ($)
Subcompact	31.2	30.1	38.9 (25)	543	36.2 (16)	513	33.3(7)	379
Compact	27.9	27.0	35.8 (28)	657	33.3 (19)	640	30.6(10)	520
Mid Size	24.9	24.1	33.8 (36)	872	30.5 (22)	789	28.2(13)	668
Large	21.2	20.5	30.3 (43)	1,087	28.8 (36)	1178	27.5 (30)	1286
Light Trucks								
Small SUVs	26.0	25.1	35.1 (35)	832	32.6 (26)	818	30.1 (16)	729
Mid SUVs	21.1	20.4	30.3 (44)	1070	28.2 (34)	1056	26.2 (24)	1000
Large SUVs	17.7	17.1	26.3 (49)	1308	25.1 (42)	1348	23.9 (35)	1367
Small Pick-ups	22.6	21.8	32.2 (42)	1031	29.8 (32)	1008	27.6 (22)	931
Large Pick-ups	18.1	17.5	28.6 (58)	1415	26.7 (47)	1466	24.9 (37)	1489
Mini Van	22.1	21.4	32.1 (45)	1092	29.9 (36)	1101	27.7 (25)	1059

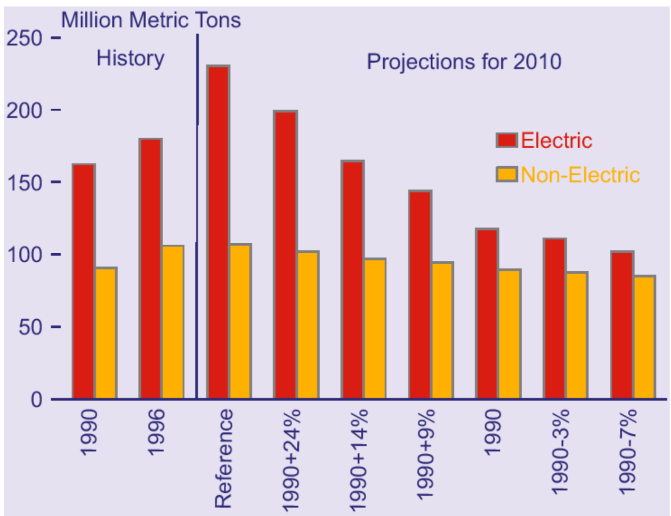
[a] Other key assumptions: (1) gasoline cost $1.50 (1999 $); (2) drive 15,600 miles first year then declining 4.5%/yr; (3) on-road fuel economy 15% less than EPA sticker; and (4) future safety and emissions standards give 3.5% fuel economy penalty. See Table 4-1.
[b] Base is before downward adjustment of - 3.5% for future safety and emissions standards.
[c] Base after adjustment for future safety and emissions standards (-3.5%)

Table 1. Break-even fuel economy analysis for 14-yer payback with 12% discount rate [34].

It is interesting to calculate how much C would be saved if half of American's second cars were replaced by HEVs. If we take 1/4 of American vehicles and cut their C production in half, we will then save $(1/2)\times(1/4)\times 32\% = 4\%$ of the total US C emissions. While this substantial, it is small compared to the Kyoto goals.

Residential[1]

Households are the largest electricity-consuming sector and account for 20% of C emissions in 1996. 63% of these emissions are attributable to fuel used for generating electricity used by households. Some noteworthy factors are the growth of all-electric homes, particularly in the South [1]. Figure 21 below shows the C emissions for 1990, 1996 and projections to 2010 for several C emission scenarios [1].



Note: Electricity emissions are from the fossil fuels used to generate the electricity used in this sector.

Sources: **History:** Energy Information Administration, *Emissions of Greenhouse Gases in the United States 1996*, DOE/EIA-0573(96) (Washington, DC, October 1997). **Projections:** Office of Integrated Analysis and Forecasting, National Energy Modeling System runs KYBASE.D080398A, FD24ABV. D080398B, FD1998.D080398B, FD09ABV.D080398B, FD1990.D080398B, FD03BLW.D080398B, and FD07BLW.D080398B.

Figure 21. Residential C emissions. Note that the main C decrease for all scenarios comes from fuel saving for electricity generation ([1], Figure 28).

Carbon in Schenectady—a Case Study

WAE has a 2700 sq ft. house in Schenectady, NY. Annual energy use is about 10,000 kWh of electricity and 1906 therms of gas. (1 therm = 10^5 BTU = 1.055 X 10^8 J). The marginal cost of electricity averages about \$0.10/kWh and marginal natural gas costs in 2000 varied from about \$0.40 to \$0.68/therm. His two cars average about 22 mpg and he drives 6,000 miles with each, thereby using a total of 545 gallons of gasoline. WAE would generally like to see investments in new technology pay off in 1-2 years and certainly in less than 5 years.

Electric power comes from a number of sources, including fossil fuel plants, nuclear and some hydro power (from Quebec), so it is difficult to gauge the C emission associated with this electricity use. Assuming an average value of 200 kg of C/MWh (Table 3 above), his home electricity use produces 2000 kg of C annually. Natural gas generates 14.55 kg of C/Million Btu ([1], Table 17), so the 1906 therms used produces 2775 kg of C. A gallon of gasoline produces about 2.4 kg of C. Then 545 gallons of gasoline produces ~1300 kg of C. Thus the total household C production, including electricity use, gas and car driving, is about 6075 kg per year.

The house has a reasonably efficient gas furnace, gas hot water heater and a gas clothes dryer. The stove and oven are electric, but these are not used a large amount of time and probably do not contribute significant cost, certainly not enough to warrant the capital cost of changing to gas. Thus it is unlikely that, at present prices of gas and electricity, any of the heating means would be changed.

References [4] and [5] say that low-emissivity windows have become popular and have constituted 35% of window sales since 1981. Home Depot has several varieties of these windows that cost about $150 including installation. Their literature claims that they will save $100-500 in home heating per year. The WAE house was built in 1965 and the existing windows were considered efficient then. The house has about 25 windows, so the capital cost of changing would be about $3750; this is not an attractive proposition. More effective would be the addition of storm windows that cost $28 each (not including installation, which might not be too difficult). There are other potential large leaks, however, such as sliding glass doors. If such changes were made, it would also be important to consider whether there is adequate air exchange in the house. Improving house heat retention by changing windows is not simple or inexpensive.

References 4 and 5 mention that refrigerator energy use has gone from 1800 kWh/yr in 1973 to a standard of 450 kWh/yr in 2001. The refrigerator in this house (~1995) uses about 1000 kWh/yr. Saving 550 kWh/yr would save about $.10 x 550 = $55 per year. This is not enough to warrant the capital cost of replacement, about $1000.

A 20 W compact fluorescent (CF) lamp that produces light equivalent to a 75 W incandescent can save 55 W. A 37 W CF lamp supposedly produces light equivalent to a 150 W incandescent bulb (highest level of a 3-way bulb) and therefore saves about 110 W. The 20 W CF costs about $10 and the 37 W lamp $14. If the 20 W lamp is on 4 hours per day, at $0.10/kWh, it will save about $8.00 per year. Thus it would take slightly more than one year to pay back its investment. Four hours use of the 37 W lamp per day would save $16.00 per year vs. the equivalent incandescent and thus will pay back in less than a year.

There are probably only about three or four lights in the WAE house that would pay back the investment in less than three years, so the prospect of buying many CF lamps is not appealing, even though the total power of all the other lamps may add up to a considerable quantity. CFs are generally larger than standard tungsten bulbs and do not fit in many lamps or ceiling fixtures. They also take time to warm up and their output can decrease substantially over their life. CFs also contain Hg, which is not environmentally friendly. Thus present prospects for saving substantial C by using large quantities of CFs are not good. Development of residential white LED lighting could change this situation provided it is not too expensive.

(The average electricity cost in the US is more like $0.06 [1] which makes adoption of electricity-saving appliances and lamps even less economically compelling.)

Changing one car to a gas-electric hybrid that gets, say, 50 mpg would save 153 gallons of gasoline and therefore 367 kg C or 6% of the household total calculated above.

It would appear, then, that readily available energy efficient strategies for the home would not produce large C emission reductions from the WAE household.

Conclusions

Global temperatures appear to be increasing over the past 40 years. The climate modeling community is convinced that increasing CO_2 has probably been an important factor in the temperature rise during that period and that increasing CO_2 will very likely be a dominant influence on global temperature for the 21st century and beyond. Applying the Kyoto Protocol to the US could introduce significant lifestyle changes and resource shifts, and implementation seems politically problematic. Further, the Kyoto Protocol will not change the global C emissions appreciably in the short run, and the C emissions control scenarios that are envisioned by the IPCC [2] may not make much difference to the temperature changes by 2100 [17, 18].

It is important to continue to invest in refining global scientific measurement capabilities as we go forward. The NRC report "Climate Change Science" says that ([40], pg 24)

> …the observing system available today is a composite of observations that neither provide the information nor the continuity in the data needed to support measurements of climate variables. Therefore, above all, it is essential to ensure the existence of a long-term observing system that provides a more definitive observational foundation to evaluate decadal- to century-scale variability and change.

We should continue to encourage the development of energy-efficient technologies through research support and government programs like "Green Lights" and "Energy Star" which publicize and encourage cost-effective, energy-efficient technologies. Most of the efficiency gains of C production in the next 5-10 years will come from improvements in electricity generation and, possibly, cogeneration. Gas-electric hybrid cars seem a good prospect for improved transportation efficiency, and it is likely that increased mileage will be required via CAFE legislation. There are a number of home technologies, such as more efficient electrical appliances, that will somewhat reduce C emissions but their integrated effect will not provide a large fraction of the Kyoto reductions. We may want to consider whether we should tilt toward energy efficiency by imposing carbon taxes while reducing other taxes in order to remain, overall, revenue neutral.

In the long run there has to be some degree of equity in energy use and C production among various parts of the world. The least disruptive way to achieve this goal and maintain a stable world polity is through technology that enables substantial use of energy while decreasing the C produced. Such technologies might include non-fossil-fuel electricity production through renewables and nuclear power, a hydrogen economy, and large-scale C capture and sequestration.

The problems of energy and global climate management are among the most important facing humankind. Discussion and debate, both internationally and within the US, must increase and involve more of the scientific community and general populace. Changes could be farreaching and sometimes painful and will therefore require a high level of patience and understanding. These issues will affect everyone and cannot be left to specialists. Experts, for their part, must help in producing better general understanding. There is a long way to go on research and development of energy-producing, energy-efficient and C-reduction technologies, and our research budgets should be shaped to recognize the importance and urgency of these topics [41].

Acknowledgements

We would like to thank Dr. A. Herzog of RAEL, University of California, Berkeley, Dr. H. Vakil of GE Research and Development Laboratory, Schenectady and Dr. William Evenson of the University of Utah for invaluable help in producing this report.

Appendix: Data Tables

Summary Indicators	1996	2010 Reference	2010 1990 +24%	2010 1990 +9%	2010 1990 -3%	2020 Reference	2020 1990 +24%	2020 1990 +9%	2020 1990 -3%
Carbon Price (1996 Dollars per Metric Ton)	**NA**	**NA**	**67**	**163**	**294**	**NA**	**99**	**141**	**240**
Delivered Energy Price (1996 Dollars per Million Btu)									
Coal	1.32	1.12	2.82	5.24	8.57	1.01	3.50	4.57	7.18
Natural Gas	4.13	3.76	4.71	6.45	8.49	3.96	5.69	6.95	8.30
Motor Gasoline	9.89	10.11	11.23	12.53	14.49	10.00	11.45	12.04	13.48
Jet Fuel	5.52	5.62	6.69	8.15	10.24	5.76	7.32	8.01	9.66
Distillate Fuel	7.84	7.81	8.91	10.50	12.71	7.67	9.21	9.79	11.49
Electricity	20.19	17.22	20.92	25.70	30.68	16.31	21.44	23.77	26.10
Primary Energy Use (Quadrillion Btu)									
Natural Gas	22.60	28.97	29.57	31.82	32.49	32.65	34.50	36.02	35.39
Petroleum	36.01	43.82	42.83	41.12	38.89	46.88	45.25	44.78	42.94
Coal	20.90	24.14	19.70	11.68	6.72	25.27	15.28	7.06	2.59
Nuclear	7.20	6.17	6.68	6.98	7.36	3.80	5.06	5.90	6.86
Renewable	6.91	7.27	7.44	7.72	8.23	7.59	8.29	9.77	11.91
Other[a]	0.39	0.80	0.25	0.25	0.23	0.83	0.26	0.26	0.25
Total	94.01	111.18	106.48	99.57	93.93	117.02	108.64	103.79	99.94
Electricity Sales (Billion Kilowatthours)	**3,098**	**3,865**	**3,696**	**3,492**	**3,286**	**4,240**	**3,972**	**3,837**	**3,718**
Carbon Emissions by Fuel (Million Metric Tons)									
Natural Gas	318	415	424	456	466	468	495	517	507
Petroleum	621	752	735	704	660	805	777	767	727
Coal	524	621	506	299	172	652	393	181	66
Total	1,463	1,791	1,668	1,462	1,300	1,929	1,668	1,468	1,303
Carbon Emissions by Sector (Million Metric Tons)									
Residential	286	337	301	238	199	375	291	224	181
Commercial	230	277	244	186	147	299	225	168	130
Industrial	476	559	519	462	418	582	505	449	405
Transportation	471	617	605	576	536	673	647	626	588
Total	1,463	1,791	1,668	1,462	1,300	1,929	1,668	1,468	1,303
Electricity Generation	517	657	567	409	312	726	519	351	246
Carbon Reductions by Sector (Million Metric Tons)									
Residential	NA	NA	37	99	139	NA	85	151	195
Commercial	NA	NA	33	91	130	NA	73	131	169
Industrial	NA	NA	41	98	141	NA	77	133	177
Transportation	NA	NA	12	41	81	NA	26	47	85
Total	NA	NA	123	329	491	NA	261	461	625
Electricity Generation	NA	NA	90	248	345	NA	207	375	481
Electricity Generation as Percent of Total	NA	NA	74	75	70	NA	79	81	77
Energy Fuel Expenditures (Billion 1996 Dollars)	**560**	**637**	**726**	**834**	**952**	**674**	**807**	**862**	**945**
Energy Intensity (Thousand Btu per 1992 Dollar of GDP)	**13.57**	**11.80**	**11.42**	**10.78**	**10.33**	**10.78**	**10.05**	**9.62**	**9.27**
Carbon Intensity (Kilograms per Million Btu)	**15.6**	**16.1**	**15.7**	**14.7**	**13.8**	**16.5**	**15.4**	**14.1**	**13.0**

[a] Includes net electricity imports, methanol, and liquid hydrogen.

NA = not applicable.

Note: Totals may not equal sum of components due to independent rounding.

Sources: **1996:** Energy Information Administration, *Annual Energy Outlook 1998*, DOE/EIA-0383(98) (Washington, DC, December 1997). **Projections:** Office of Integrated Analysis and Forecasting, National Energy Modeling System runs KYBASE.D080398A, FD24ABV.D080398B, FD09ABV.D080398B, and FD03BLW.D080398B.

Table A1 (Ref. [1], Table 2). Summary data for different C reduction scenarios. "Reference" refers to scenario of no reduction, 2010 C emission is +34% above 1990 level. The "carbon price" figures are imposed as carbon taxes or permits. The current C base cost is approximately $450/tonne. Looking at the first section (Delivered Energy Price…), coal cost $1.32 per million BTU in 1996 and would cost $8.57 per million BTU in 2010 if a C price of $294 per tonne were imposed. (The heat of combustion of octane is 48.4 MJ/kg = 45,800 BTU/kg [21]).

Table ES1. Selected Variables in the Carbon Reduction Cases, 1996 and 2010

Variable	1996	2010						
		Reference	1990 +24%	1990 +14%	1990 +9%	1990	1990 -3%	1990 -7%
U.S. Carbon Emissions								
(Million Metric Tons)	1,463	1,791	1,668	1,535	1,462	1,340	1,300	1,243
Emissions Reductions								
(Percent Change From Reference Case)	—	—	6.9	14.3	18.4	25.2	27.4	30.6
Total Energy Consumption								
(Quadrillion Btu)	93.8	111.2	106.5	101.9	99.6	95.2	93.9	91.7
(Percent Change From Reference Case)	—	—	-4.2	-8.4	-10.4	-14.4	-15.6	-17.5
Carbon Price								
(1996 Dollars per Metric Ton)	—	—	67	129	163	254	294	348
Carbon Revenue[a]								
(Billion 1996 Dollars)	—	—	110	195	233	333	374	424
Gasoline Price								
(1996 Dollars per Gallon)	1.23	1.25	1.39	1.50	1.55	1.72	1.80	1.91
(Percent Change From Reference Case)	—	—	11.2	20.0	24.0	37.6	44.0	52.8
Average Electricity Price								
(1996 Cents per Kilowatthour)	6.8	5.9	7.1	8.2	8.8	10.0	10.5	11.0
(Percent Change From Reference Case)	—	—	20.3	39.0	49.2	69.5	78.0	86.4
Actual Gross Domestic Product[b]								
(Billion 1992 Dollars)	6,928	9,429	9,333	9,268	9,241	9,137	9,102	9,032
(Percent Change From Reference Case)	—	—	-1.0	-1.7	-2.0	-3.1	-3.5	-4.2
(Annual Percentage Growth Rate, 2005-2010)	—	2.0	1.8	1.7	1.6	1.4	1.3	1.2
Potential Gross Domestic Product								
(Billion 1992 Dollars)	6,930	9,482	9,469	9,455	9,448	9,429	9,420	9,410
(Percent Change From Reference Case)	—	—	-0.1	-0.3	-0.4	-0.6	-0.7	-0.8
(Annual Percentage Growth Rate, 2005-2010)	—	2.0	2.0	1.9	1.9	1.9	1.9	1.9
Change in Energy Intensity								
(Annual Percent Change, 2005-2010)	—	-1.0	-1.6	-2.0	-2.1	-2.7	-2.8	-3.0
(Percent Change From Reference Case)	—	—	55.6	96.4	108.2	161.8	177.0	199.0

[a]The carbon revenues do not include fees on the nonsequestered portion of petrochemical feedstocks, nonpurchased refinery fuels, or industrial other petroleum.

[b]Carbon permit revenues are assumed to be returned to households through personal income tax rebates.

Source: Office of Integrated Analysis and Forecasting, National Energy Modeling System runs KYBASE.D080398A, FD24ABV.D080398B, FD1998.D080398B, FD09ABV.D080398B, FD1990.D080398B, FD03BLW.D080398B, FD07BLW. D080398B.

Table A2. C emissions, fuel prices and GDP. Projections of prices for various C reduction scenarios, 1996-2020 [Ref [1], Table. ES1].

Technology	1997 gen market share	1997 avg. grams carbon / kWh	Possible future improvement	Issues/comments
Coal boilers	56%	260	New plant efficiency could be as high as a third greater than the efficiency of existing plants Existing plant efficiency could be improved but to a lesser extent Carbon sequestration	Few new coal plants are currently planned Existing plants are cheapest source of fossil power Refurbishments are costly Depending on pending environmental constraints, older plants may be retired Seq. in early research stage
Coal IGCC	~0	210	Possible combination with fuel cell yields high efficiency and carbon separation achieving near zero carbon and criteria air pollutant emissions	Close to commercial 3 commercial demonstration plants operating in U.S.
Gas Turbine	<5%	170	New plant efficiency >40% efficiency; current plants ≈32%	Largely peak load (with some intermediate), thus has lower impact on total emissions
Gas combined cycle	<4%	100	Market share can be substantially increased over time New plant efficiencies could increase to 60% to 70% with a ternary cycle; current models are 43% –57% efficient With carbon separation could achieve near zero carbon	Designed for intermediate and base load; could replace retiring coal plants and inefficient gas plants Large resource base Fuel deliverability and cost may become issue in future
Fuel cells	0%	>=0 depending on fuel source	Can be combined with other cycles With carbon separation could achieve carbon and criteria air pollutant emissions near zero	First cost needs to be reduced further Technology improvements needed
Nuclear	20%	0	Improved efficiency and life extension of current plants possible at low cost New small plants may better meet market needs	Public concern with safety Spent fuel storage and disposal could limit future operations More than 50% of plants require license renewal by 2020
Hydro	10%	0	Increased efficiency and enhanced environmental performance with advanced technology	Large potential (60 GW) Concerns with environ-mental impacts from public and natural resource management agencies
Wind	<1%	0	Costs competitive on kWh basis in near future in some markets	1998 growth rate of 35% worldwide Intermittency may limit role
Biomass cofiring	<1%	~0 for biomass portion	Use can be increased relatively easily to 2 – 4 % of coal generation	Requires biomass collection infrastructure; negligible coal plant retrofits required at low levels of biomass to coal.
Geothermal Hydrothermal	<1%	0	Resource identification	Competitive today at good resource site; resources limited
Photovoltaics	0	0	75% cost reductions possible in long term (EPRI, 1997)	Large 2020 potential in buildings assuming net metering
Solar thermal	<1%	0	Limited cost-reduction potential	Only southwestern U.S.

Table A3. Present status and potential for various electricity-generating technologies (Ref. [5], table 7.1).

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