# Energy intensity decline implications for stabilization of atmospheric $CO_2$ content.

by

H. Douglas Lightfoot*, Mechanical Engineer (retired)

and

Christopher Green*, Dept. of Economics, McGill University

*McGill Centre for Climate and Global Change Research ($C^2$GCR)

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## Abstract

We estimate the appropriate rate of world average annual energy intensity decline to be used in calculating the amount of carbon-free energy required to stabilize the level of $CO_2$ in the atmosphere at some level, such as 550 ppmv in 2100.

We distinguish between the roles played by energy efficiency and long term sectoral changes, i.e., shifts in economic activity from high energy intensity sectors or industries to low energy intensity sectors or industries, such as the service industries. Improvements in energy efficiency comprise both those that arise from advances in technology and improved procedures and those that arise from wider adoption of the most efficient technologies available.

Our procedure is to estimate the potential energy efficiency increase for the 110 years between 1990 and 2100 for world electricity generation (38% of world energy consumption in 1995), transportation (19%) and for residential, industrial and commercial uses (43%). Our result shows an overall average decline in energy intensity in 2100 to 40.1% of what it was in 1990. This is equivalent to an average annual rate of energy intensity decline of 0.83% for 110 years.

Sensitivity analysis shows that the impact of sectoral changes on the average annual rate of decline in energy intensity could add between 0.16% and 0.30% to the 0.83% attributable to improvements in energy efficiency. Together, energy efficiency improvements and sectoral changes are estimated to allow an average annual rate of decline in energy intensity of 1% to 1.1% for the 110 year period 1990 to 2100.

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## Introduction

Our argument that new sources of energy are needed if global climate change is to be averted was initially presented as a Centre for Climate and Global Change Research Report ($C^2GCR$) No. 92-6(12) in 1992, and has since appeared in subsequent articles and presentations. In our second $C^2GCR$ report No. 2001-1(13) in 2001, we quantify the amount of carbon-free energy required annually to stabilize the level of $CO_2$ in the atmosphere by building on the framework developed by Hoffert et al. (1998)(1). It also touches on the issue of what is the attainable energy efficiency for 110 years from 1990 to 2100.

This report, $C^2GCR$ 2001-7, is a detailed analysis of the attainable average annual energy intensity decline from 1990 to 2100. The main component of energy intensity decline is energy efficiency, which when combined with sectoral changes gives a measure of overall energy intensity decline. Sectoral changes are defined as shifts in economic activity from high energy intensity sectors or industries to low energy intensity sectors or industries, such as most service industries, thereby reducing the energy required per unit of GDP.

The conclusion from the analysis in $C^2GCR$ 2001-7 that ".... the average annual energy intensity decline is between 1.0 and 1.1%" is consistent with our suggestion in $C^2GCR$ report 2001-1, "...that, on average, world energy consumption per unit of output reaches a lower limit of about one third the level in 1990, which is equivalent to an annual average increase in energy efficiency of 1% from 1990 to 2100." It also supports the work of Hoffert et al.(1) in calculating the amount of carbon-free energy that would be required in 2100 to stabilize the level of $CO_2$ in the atmosphere in 2100, i.e., Given the population and GDP growth rate assumptions employed by Hoffert et al., the 37 TW (1188 EJ) they calculated by assuming a 1% annual average energy intensity decline for 110 years is a reasonable estimate of what will be needed.

A popular view held by many scientists, environmentalists, politicians and the general public is that energy problems affecting climate change can be solved by conservation, increases in energy efficiency and the use of renewable energies such as hydro, biomass, wind and solar. We have shown in $C^2GCR$ reports 92-6 and 2001-1 that renewable energies require too much land to replace fossil fuels on the scale needed. In $C^2GCR$ report 2001-1, we showed that new, large sources of carbon-free energy are needed if we are to stabilize the level of $CO_2$ in the atmosphere at some level, such as 550 ppmv. In this report we estimate that there are upper limits on attainable energy efficiency increases that will limit the long term rate of decline in energy intensity.

The multidisciplinary McGill Centre for Climate and Global Change Research ($C^2GCR$) was created in March 1990. Its current membership is composed of 17 faculty members from eight departments, i.e. Atmospheric and Oceanic Sciences, Biology, Chemistry, Geography, Natural Resource Sciences, and Economics at McGill University and, from the Université du Québec à Montréal (UQAM), Sciences de la terre and from the Université de Montréal, Géographie. The web site is: http://www.mcgill.ca/ccgcr/. Approximately 60 graduate and postdoctoral students are supervised by faculty of the Centre.

# Energy intensity decline implications for stabilization of atmospheric $CO_2$ content.

## Outline of the general problem

The build-up of greenhouse gases in the atmosphere threatens to alter the world climate by raising average global temperature and changing precipitation patterns. The economic, environmental, and social costs of climate change are difficult to estimate, but are expected to grow as global warming proceeds. It is widely agreed that in the 21st century, the various nations of the world must make a major effort to reduce greenhouse gas emissions, especially from the burning of fossil fuels.

A reduction in greenhouse gas emissions sufficient to stabilize the atmospheric concentration of $CO_2$, the main greenhouse gas, at 550 ppmv, twice the pre-industrial concentration, will require a combination of improvements in energy efficiency, or a reduction in energy intensity, and increases in the availability and use of carbon-free sources of energy, including renewable energies and conservation.

Hoffert et al. in the article "Energy implications of future stabilization of atmospheric $CO_2$ content", Nature, Vol. 395, 29 Oct. 1998, pp 881-884**(1)**, demonstrated that the amount of carbon-free energy required to stabilize atmospheric $CO_2$ is inversely related to the rate of decline in energy intensity. The paper predicted that about 37 TW (1188 EJ)**(2)** of carbon-free primary power would be required to stabilize atmospheric $CO_2$ at twice the pre-industrial concentration.

In this paper we deal with only one aspect of the Hoffert et al. analysis, i.e., the appropriate rate of energy intensity decline to be used in computing the required amounts of carbon-free energy. We show that there are indeed limits on energy efficiency, and these limits have important implications for the long term rate at which energy intensity can be expected to decline. We find that the assumed 1% average annual rate of energy intensity decline for 1990 to 2100, equivalent to a 66% decline from the current global average energy intensity level, which Hoffert et al. took as their central case, will be difficult to sustain for a century or more. This means the 37 TW (1188 EJ) of carbon-free power that Hoffert et al. estimated would be required to stabilize the atmospheric concentration of $CO_2$ at twice its pre-industrial level may be on the low end of the plausible range of carbon-free power required for stabilization.

Some readers may find it easier to understand the term "energy efficiency increase per unit of output" rather than “energy intensity decline per unit of output”. The relationship between them is in Table 1, which shows in the right hand column the percentage decline in energy intensity implied by a given percentage improvement in energy efficiency. If we ignore sectoral share changes, the two terms describe the same thing, but in slightly different ways. Energy efficiency increases may be achieved by inventing and implementing new technology and by implementing current technology, such as replacing old refrigerators with new, more energy efficient models. Thus, in this paper, improvements in energy efficiency comprise both those that arise from advances in technology and improved procedures with those that arise from wider adoption of the most efficient technologies available.

We also distinguish between the roles played by energy efficiency and long term sectoral changes that reduce the relative importance of energy intense industries and activities. For example, the contribution to world Gross Domestic Product (GDP) of high energy intensity industries such as iron and steel, chemicals, etc., is expected to decline over time in favor of low energy intensity industries, such as various service industries. When combined, the rates of improvement in energy efficiency and sectoral change determine the rate at which energy intensity declines.

**Table 1. Percent energy efficiency increase vs percent energy intensity decline for the same final effect**

| Energy efficiency increase % | Energy intensity decline % |
|---|---|
| 33 | 25 |
| 50 | 33 |
| 75 | 43 |
| 100 | 50 |
| 150 | 60 |
| 200 | 67 |
| 300 | 75 |

Some investigators have looked to substantial increases in the rate of decline of energy intensity to reduce the required amount of carbon-free power. The choice of average annual energy intensity decline has a profound effect on the amount of carbon-free energy required. For example, to stabilize the atmospheric concentration of $CO_2$ in 2100 at 550 ppmv, an average annual rate of energy intensity decline of 0.63% sustained for 110 years requires about 60 TW (1890 EJ/yr)**(1)** of carbon-free energy. Increasing the average annual rate of decline to 1%, the rate employed by Hoffert et al., reduces the carbon-free energy requirement to about 37 TW (1188 EJ/yr). A further increase to 2% reduces the carbon-free energy requirement to about 7 TW (220 EJ/yr).

To better illustrate the trade off between energy intensity decline and carbon-free energy required to stabilize atmospheric $CO_2$ we reproduce as our Figure 1 a slightly modified form of Figure 3 from Hoffert et al. The figure illustrates the sensitivity of carbon-free energy requirements to the average annual rate of energy intensity decline over 110 years.

Hoffert et al., used a 1% average annual decrease in energy intensity based on historical records and extrapolated it to 2100. They had some doubts about the rate of energy intensity decline that might be achieved over the 110 year period, 1990 to 2100, as evidenced in the following quotation, "For a 2% per year compounded growth, the carbon-free power required remains modest even by the year 2100. But 2% may be impossible to sustain over the next century...."(3). However, Hoffert et al. did not pursue possible limits of energy intensity decline further.

The attainable rate of decline in energy intensity is the focus of this paper. Using the benchmark of atmospheric $CO_2$ stabilization at 550 ppmv by 2100, we ask, What is the maximum contribution of energy intensity decline toward stabilization of $CO_2$ level in the atmosphere? We use the energy mix of 1995 and apply estimates for energy intensity decline limits to 2100 and calculate an average annual energy intensity decline for the world.

Concern about energy efficiency is not new. The Industrial Revolution provided an impetus to improve energy efficiency as did the "oil crisis" of the 1970s. The energy efficiency in generating electricity has been studied and innovations applied in a systematic manner to the point where steam boilers and electrical generators have been close to maximum efficiency for more than half a century(4). Similarly, the most efficient domestic hot water and home heating systems have been close to maximum efficiency for a few decades. Although it is important to recognize that some energy efficiencies cannot be increased much further, there is always room for adoption of the most efficient methods.

To simplify the calculations, world energy consumption in 1995 is split into three parts: (1) generation of electricity (38% of world energy consumption in 1995); (2) fossil fuels used for transportation (19%); and (3) residential, industrial and commercial uses of energy (43%).

## Electricity

The actual average energy efficiency of electricity generation in 1995 for the world was 28.9% as given in Table 2A. Energy efficiency is defined as the amount of energy in the form of electricity produced by the generating station divided by the amount of energy in the fuel that is consumed to generate that electricity. Although the average thermal efficiency of electricity generation from fossil fuels in the US in 1999 was estimated to be 32.5%(5), thermal efficiencies throughout the world range from about 20% to about 40%(6). Average nuclear stations have an electricity generating efficiency ranging from 29% to 38%, with the common light water reactor operating at about 34%(6).

**Table 2A. World electricity production in 1995(7)**

| | 1995 | Units |
|---|---|---|
| Total world energy consumption | 385.7 | EJ |
| World energy consumption used for electricity generation | 147.1 | EJ |
| World consumption of electricity ( 8) | 42.5 | EJ |
| Average world energy efficiency for electricity generation | 28.9 | % |
| Percent of world energy consumption used for electricity generation | 38.1 | % |

How much improvement in the electricity generating efficiency can be expected between 1990 and 2100? Hydro is already at its maximum average efficiency of about 85%(9). Nuclear appears to have some potential for energy efficiency improvement(10). If nuclear fusion ever becomes viable, it is likely to have about the same energy efficiency as nuclear fission when used as a heat source to generate electricity. Coal and oil fired generating stations are very close to maximum energy efficiency. Natural gas fired generating stations have the potential for energy efficiencies in the range of 50% to 60% by using combined cycle technology(11).

**Table 2B. World electricity production by fuel in 1995, estimated for 2100**

| A<br>Type of energy(7) | B<br>Energy source in 1995 EJ | C<br>Energy source in 1995 % | D<br>Assumed energy source in 2100 % | E<br>Estimated average energy efficiency in 2100 % | F<br>Estimated contribution to average energy efficiency in 2100 D x E % |
|---|---|---|---|---|---|
| Oil | 13.8 | 9.4 | 0 | - | - |
| Natural Gas | 23.4 | 15.9 | 50 | 60 | 30.0 |
| Coal | 53.5 | 36.4 | 10 | 35 | 3.5 |
| Nuclear | 24.6 | 16.7 | 25 | 40 | 10.0 |
| Hydro | 27.4 | 18.6 | 9 | 85 | 7.7 |
| Other | 4.4 | 3.0 | 6 | 40 | 2.4 |
| Total | 147.1 | 100.0 | 100 | - | 53.6 |
| Increase in energy efficiency from 1995 to 2100, (53.6 - 28.9)/28.9 | | | | | 85.3% |
| Decrease in energy intensity from the 1995 level to 2100 | | | | | 46.0% |
| Energy intensity in 2100 as percentage of the 1995 level | | | | | 54.0% |

In a gas fired combined cycle generating station, natural gas is used to drive a gas turbine and the exhaust gases are used to generate steam to drive a steam turbine. The thermal efficiency of gas and steam turbines is a function of the temperature difference between the inlet temperature and the outlet temperature. Combining gas and steam turbines takes advantage of the high input temperature of a gas turbine and the low outlet temperature of a steam turbine. The temperature of the hot gas entering a gas turbine is limited by the materials of construction properties of the gas turbine blades. The low temperature of a steam turbine is limited by the temperature of the cooling water used to condense the exhaust steam. This combination maximizes the overall temperature difference, thereby maximizing the thermal efficiency. Coal is not used as a fuel for gas turbines because the ash erodes the turbine blades. It may be possible to use some types of oil to fuel gas turbines and obtain the benefits of combined cycle technology.

In Table 2B, the mix of energy input to electricity generation is assumed to change considerably between 1990 and 2100. By 2100, total world energy consumption is estimated to increase between three and four times the 1990 level. The demand for electricity may well increase significantly faster because about one third of the world's population is not connected to an electricity grid, and because there are no substitutes for electricity.

About one half of the world's hydro power has already been harnessed and if the remainder were developed by 2100, the share of hydro would fall from the present 18% to about 9% of world electricity production. For purposes of this analysis, nuclear fission has been assumed to continue to grow and to generate 25% of total world electricity by 2100. "Other", which is mostly some form of biomass with a little wind and solar energy, may increase its share beyond the present 3% to, perhaps, 6% but, even so, it will remain relatively small for reasons discussed at length elsewhere**(12)(1)(14)(13)**. Little efficiency improvement can be expected from wind turbines, which are now at about 80% of the maximum theoretical efficiency**(14)**. The efficiency of solar photovoltaic cells might increase from the present 15% to between 20% to 28% in unconcentrated sunlight**(12)**. Although wind and solar energies are renewable and carbon-free, their efficiency is still important because of the very large number of wind turbines and the large amount of land area that would have to be covered with solar cells to collect more than a token portion of the estimated 37 TW (1188 EJ) of carbon-free energy needed to stabilize atmospheric $CO_2$ at 550 ppmv in 2100.

Because we are focussing on energy efficiency rather than the carbon content of energy, in Table 2B we have assumed, for purposes of analysis, that the share of fossil fuel energy used to generate electricity would remain at about 60%. A much smaller share for fossil fuels and a larger share for carbon-free energy sources would not materially affect the energy efficiency results.

In Table 2B, natural gas would expand from generating 15.9% of world electricity in 1995 to 50% in 2100, coal would drop from 36.4% to 10%, and oil would drop from 9.4% to zero. This is an optimistic scenario as it is unlikely by 2100 that 87% all of the world's fossil fuelled generating plants could be fuelled by natural gas. The amount of natural gas needed annually would be on the order of fifteen to twenty times that used in 1995. In some parts of the world, natural gas is not available in sufficient quantities. Further, electricity generating stations that are being built today have an expected life of forty to fifty years. Thus, it will be decades before all existing facilities could be replaced and the full impact of efficient new technologies realized. If 87% of all fossil fuel fired electricity generating stations could be converted to natural gas, then based on 1995 electricity production, carbon emissions from electricity generation would drop by about 25% and world carbon emissions would drop by about 10%. However, the expected growth in electricity production from 1995 to 2100 of three to four times would more than offset these reductions.

Cogeneration involves the recovery of thermal energy that is normally lost or wasted. Some specific industrial applications of cogeneration have achieved efficiencies in the 40% to 50% range. However, it is difficult to obtain large and/or consistent benefits from cogeneration because the normally lost or waste heat cannot be stored until needed. Thus, it is necessary to try to balance the amount and timing of the loads between electricity generation and heat utilization. This is difficult as evidenced by the fact that only about 6% of total US electricity generating capacity includes some type of cogeneration system, in such diverse industries as manufacturing, mining and refining(15). Fossil fuel electricity generating stations currently use waste heat to preheat combustion air and boiler feed water. Cogeneration is likely to remain a very small contributor to improved energy efficiency and has not been considered as a significant contributor in this analysis.

At this point, it is necessary to discuss the potential of hydrogen powered fuel cells to produce the large amounts of electricity consumed annually by the world. Hydrogen is the best fuel for fuel cells because hydrocarbon fuels leave carbon deposits which prevent the cells from operating efficiently(16).

Solid oxide fuel cells are available with 70% efficiency, and with utilization of waste heat, fuel cells can reach 85% efficiency(17). If, at 70% efficiency, these fuel cells could use natural gas directly as a fuel(18), then these fuel cells would be energy efficiency competitive with natural gas fuelled combined cycle generating plants.

But, if the fuel cell requires hydrogen, which is first made from fossil fuels, then it will not be energy competitive with natural gas fired combined cycle generating stations. For example, most hydrogen today is made by steam reforming of natural gas with conversion efficiency to hydrogen of not more than about 66%. Thus, the efficiency of electricity production by 70% efficient fuel cells using hydrogen reformed from natural gas would be 0.66 x 0.70 = 46%, which is considerably less than the 60% efficiency of combined cycle natural gas fuelled generating stations.

In summary, from Table 2, the average efficiency of electricity generation in 2100 is estimated at 53.6% versus 28.9% in 1995, an increase in energy efficiency of 85.3%. The energy intensity decrease is 46% and the energy intensity in 2100 for the generation of electricity is 54% of that in 1995.

## Transportation

Transportation was estimated to consume about 19% of world energy in 1995(19). Almost all of the transportation energy was supplied by fossil fuels. The breakdown by method of transportation figures are for the US(20) because comparable figures for the world do not appear to be available. The resulting energy efficiency will be higher than what might reasonably be expected because the percentage of cars and light trucks will be lower in the world than for the US, and large cars and light trucks, so prevalent in the US, have the largest potential for energy efficiency increase.

The recent introduction of gasoline/electric, or hybrid electric cars(21), where the gasoline engine runs mainly at maximum efficiency to generate electricity which is stored in a battery, or drive the car when needed, has promise to double the average fuel rate of new cars from a peak in about 1988 of 8.6 litres per 100 km (27.5 miles per US gallon(22)). A further efficiency increase of 115%(23) may be possible by improvements to current four stroke engines, continuously variable transmissions, light weight materials, reduced rolling resistance and improved aerodynamics. The potential improvements in energy efficiency for light trucks is much more limited than for passenger cars(23) because their design is more suited to carrying loads rather than passengers. The doubling of efficiency by hybrids plus 115% for other efficiency increases comes to an overall efficiency increase of 215%. For purposes of this analysis we have assumed that a 300% increase in energy efficiency over that in 1990 for 2100 is possible. This would imply a maximum new passenger car fuel rate of 2.1 litres/100 km (110 miles per US gallon) by 2100.

The size and weight of heavy trucks is limited by weight and size restrictions on highways. We assume no significant change in the weight carrying capacity of large trucks and no significant relaxation of size restrictions on the world's highways. Improvements in energy efficiency must, therefore, come from propulsion systems**(21)** and reductions in air and rolling resistance. For purposes of this analysis we have used a 100% increase in energy efficiency of large trucks from 1990 to 2100.

**Table 3. US transportation energy by method of transportation**

| A | B US(20) transport-ation energy 1995 % | C Increase in energy efficiency 1990 to 2100 % | D Decline in energy intensity from 1990 to 2100 % | E Energy intensity in 2100 as % of 1990 % | F Contribution to overall energy intensity in 2100 B x E % |
|---|---|---|---|---|---|
| Cars and light trucks | 60 | 300 | 75 | 25 | 15.0 |
| Trains, trucks, and ships | 20 | 100 | 50 | 50 | 10.0 |
| Aircraft | 13 | 100 | 50 | 50 | 6.5 |
| Other | 7 | 300 | 75 | 25 | 1.8 |
| Totals | 100 | - | - | - | 33.3 |

Trains have the advantage of the low rolling resistance of steel wheels on steel rails. The static friction between the steel wheels of a locomotive and the rail is also low and limits the pulling power of each set of wheels. Locomotives are deliberately made heavy to increase the friction force on the rails to maximize the pulling force on the draw bar. The diesel/electric propulsion system applies the optimum torque on the wheels to maximize the draw bar force and prevent slipping of the wheels on the rails. Although all of these systems are well developed, for purposes of this analysis we have used a 100% increase in efficiency from 1990 to 2100.

The power to drive a ship at a given speed increases as the square of the size and the carrying capacity increases as the cube. Thus, there is an energy advantage for larger and larger ships as evidenced by the development of large super tankers, which require special port facilities. Most shipping is limited by the size of port and canal facilities. It is unlikely that this will change significantly, if at all, so that the average size of ships cannot increase significantly. Large increases in the efficiency of ship propulsion systems**(21)** and in reducing drag from improved hull shapes and anti-fouling methods do not appear likely. For purposes of this analysis we have used 100% efficiency increase from 1990 to 2100.

Similarly to ships, large aircraft are more efficient than smaller ones, hence, the trend to larger and larger aircraft. Limitations on the size of aircraft are route traffic patterns, runway construction and airport facilities. With these constraints, it is unlikely that the average size of aircraft will increase substantially by 2100. Most increases in energy efficiency will continue to come from light weight materials and engine efficiency(21). For purposes of this analysis we have used 100% efficiency increase from 1990 to 2100.

The "Other" category appears to be about half heavy fuel oils for marine use and half unidentified uses. Because of the uncertainty, we have assumed an energy efficiency increase of 300%.

The overall energy intensity per unit of output for world transportation in 2100 is estimated at 33.3% of what it was in 1990.

## Residential, Industrial and Commercial

The remaining 43% of world energy consumption has been broken into three categories usually found in the literature: residential, industrial and commercial. The percentages of each are a composite of estimates from one Canadian(24) and one US reference(25). There appears to be little, if any, data available for the world in the detail that is available for Canada and the US. Therefore, we have used US data as a basis in making estimates for the world for residential and industrial energy use, and have assumed that commercial has the same potential for energy efficiency improvement as industrial.

### Residential

Residential energy consumption in the US is given in Table 4(26) and is based on the amount of site electricity, i.e., the amount of electricity consumed within the housing unit. As there was no data about world residential energy consumption with the detail of the US data, we used the US data as a base and estimated what might be the residential energy consumption for the world. The purpose was to determine whether or not the 232.0% energy efficiency increase estimated for the US between 1997 and 2100 was reasonable. The result is an estimated energy efficiency increase for the world of 282.4% from 1997 to 2100. For purposes of subsequent calculations, we used 300% as the energy efficiency increase for the world from 1997 to 2100.

Space heating and air conditioning both include electricity use. Only a minor part of the estimated increase in energy efficiency to 2100 is based on increased efficiency of furnaces, heaters and air conditioners because the energy efficiency of these items is fairly well developed. For example, the efficiency of forced air house furnaces was in the range of 70% to 90% in the 1940s(27). The major part of the increase is from improved energy efficiency of windows, reduced air infiltration, better insulation and replacement of less energy efficient heating and cooling systems. As the split between space heating and cooking is not known for the world and these might be relatively large items for much of the world, energy efficiency increases are estimated as the same for each, i.e., 300%.

Energy efficiency increases for heating water will come mainly from better storage tank and piping insulation and, possibly, from combined space and water heating systems. The energy efficiency of refrigerators has increased 300% since the 1974(28) and most of the improvement in energy efficiency is likely to come from replacement of old, less energy efficient models.

Lighting, which represents less than 4% of US residential energy consumption, has potential for large increases in energy efficiency mainly through wider use of the current most efficient light bulbs and fixtures. Although cooking and clothes dryers are in the "electricity only" group, a small amount of other energy is used for both of these.

**Table 4. Residential energy consumption for the US and the world**

| | United States residential[(a)] | | | World residential[(b)] | |
|---|---|---|---|---|---|
| A | B Energy consumed in 1997 % | C Potential increase in energy efficiency to 2100 % | D Contribution to increase in energy efficiency improvement 1997 to 2100 B x C % | E Energy consumed in 1997 % | F Contribution to increase in energy efficiency improvement 1997 to 2100 E x C % |
| Includes electricity | | | | | |
| Space heating | 51.0 | 300 | 153.0 | 69.5 | 208.5 |
| Air conditioning | 4.0 | 200 | 8.0 | 0.4 | 0.8 |
| Water heating | 19.0 | 100 | 19.0 | 6.0 | 6.0 |
| Refrigerators | 5.3 | 300 | 15.9 | 0.1 | 0.3 |
| Electricity only: | | | | | |
| Lighting | 3.8 | 300 | 11.4 | 0.9 | 2.7 |
| Cooking | 1.2 | 300 | 3.6 | 20.0 | 60.0 |
| Color TV | 1.2 | 300 | 3.6 | 0.4 | 1.2 |
| Freezers | 1.5 | 300 | 4.5 | 0.1 | 0.3 |
| Clothes dryers | 2.4 | 100 | 2.4 | 0.6 | 0.6 |
| Other appliances | 10.6 | 100 | 11.6 | 2.0 | 2.0 |
| Totals | 100.0 | - | 232.0 | 100.0 | 282.4 |
| Energy efficiency increase 1997 to 2100 | | | 232.0 | - | 282.4 |
| Energy intensity decline from 1997 to 2100 | | | 70% | - | 74% |
| Energy intensity in 2100 as % of 1997 level | | | 30% | - | 26% |

Sources: (a) “A look at residential energy consumption in 1999", November 1999, EIA(26)
(b) our estimate, see text.

It is likely that the proportions of energy used for space heating and cooking are quite different for the world than for the US. The proportion of electrical appliances for the world is much less than that for the US, if for no other reason than about one third of the world's population is not connected to an electricity grid. It is also likely that the proportions of the various end uses will change as time progresses and the picture for the world in 2100 may well be closer to that of the US at present.

Overall residential energy efficiency for the world is estimated to increase by 300%, an energy intensity decline of 75% to an energy intensity of 25% of the 1990 level, for the period 1990 to 2100.

## Industrial

Table 5 shows how energy was used in the chemical industry in the US in 1994(29), and was used as a base because the information is the most detailed and the most complete of the industries that were readily available. As there was no detailed data about how world industry used energy, we made our own estimate of how energy might have been used by all world industry in 1994 using the same breakdown as for the US chemical industry. The purpose was to determine whether or not the 119% energy efficiency increase estimated for the US chemical industry between 1994 and 2100 was a reasonable estimate that might be applied to the world. The result for the world was an estimated energy efficiency increase of 145% from 1994 to 2100. Because our estimate of energy efficiency improvement for world industry may be low, we used 200% as the energy efficiency increase for world industry from 1994 to 2100. This implies a decline in energy intensity by 2100 to 33% of that in 1994(30

**Table 5. US and world industrial energy consumption**

| | US chemical industry(a) | | | World industry(b) | | |
|---|---|---|---|---|---|---|
| A | B Energy consumed in 1994 % | C Potential increase in energy efficiency to 2100 % | D Contribution to increase in energy efficiency improvement 1994 to 2100 B x C % | E Energy consumed in 1994 % | F Potential increase in energy efficiency to 2100 % | G Contribution to increase in energy efficiency improvement 1994 to 2100 E x F % |
| Boiler fuel | 43 | 100 | 43 | 15 | 100 | 15 |
| Process heat & cool | 27 | 100 | 27 | 15 | 100 | 15 |
| Machine drive | 13 | 100 | 13 | 25 | 100 | 25 |
| Other | 8 | 200 | 16 | 20 | 200 | 40 |
| Facilities | 2 | 200 | 4 | 20 | 200 | 40 |
| Electro-chemical | 2 | 300 | 6 | 0 | 300 | 0 |
| Not reported | 5 | 200 | 10 | 5 | 200 | 10 |
| Totals | 100 | - | 119 | 100 | - | 145 |
| Energy efficiency increase 1994-2100 | | | 119 | - | - | 145 |
| Energy intensity decline 1994 - 2100 | | | 54% | - | - | 59% |
| Energy intensity in 2100 as % 1994 | | | 46% | - | - | 41% |

Sources: (a) Energy Use, Chemical Industry Analysis Brief, Heat and Power Consumption by End Use, 1994(29)
(b) our estimate, see text.

## Commercial

Because we had virtually no evidence about world commercial energy consumption, we have assumed that commercial energy consumption is much like that of industrial. Thus, for purposes of this analysis, we have used an overall increase in energy efficiency per unit of output of 200%, for a reduction in energy intensity to 33% of that in 1990.

## Summary of results for residential, industrial and commercial

Table 6 shows that the energy intensity for the combination of residential, industrial and commercial is estimated at 31% of what it was in 1990, i.e., Column F.

**Table 6. Summary of results for residential, industrial and commercial sectors**

| A | B Portion in 1995[24][25] % | C Increase in energy efficiency 1990-2100 % | D Decline in energy intensity from 1990 to 2100 % | E Energy intensity in 2100 as % of 1990 % | F Contribution to energy intensity in 2100 B x E % |
|---|---|---|---|---|---|
| Residential | 28 | 300 | 75 | 25 | 7.0 |
| Industrial | 50 | 200 | 67 | 33 | 16.67 |
| Commercial | 22 | 200 | 67 | 33 | 7.33 |
| Totals | 100 | - | - | - | 31.0 |

## Average annual world energy intensity decline

Table 7 combines the estimates of energy intensity decline for electricity generation, transportation and residential, industrial and commercial to provide an estimate of the weighted average increase in energy efficiency and decline in energy intensity.

**Table 7. Summary table showing calculated average energy intensity per unit of output in 2100 as a percentage of what it was in 1990.**

| A | B Portion of world energy consumption in1995 % | C Energy intensity in 2100 relative to 1990 % | D Contribution to energy intensity in 2100 B x C % |
|---|---|---|---|
| Electricity generation - Table 2 | 38 | 53.9 | 20.5 |
| Transportation (fossil fuels) - Table 3 | 19 | 33.3 | 6.3 |
| Residential, Industrial and Commercial - Table 6 | 43 | 31.0 | 13.3 |
| Totals | 100 | - | 40.1 |
| Average annual energy intensity decline from energy efficiency | | | 0.83% |

Electricity generation consumed 38% of world energy in 1995, the largest single use of energy. Although major reductions in energy intensity are possible in transportation, residential, industrial and commercial, there are limits on improvement in energy efficiency for electricity generation, a sector which is likely to increase in relative importance and limit the overall world energy intensity decline.

The weighted average energy intensity decline due to energy efficiency improvement is estimated for 2100 at 40.1% of the level in 1990. This is equivalent to an average annual rate of energy intensity decline of 0.83% for 110 years**(30)**.

## Sectoral share changes in energy using activities

If the share of global activity accounted for by the highly energy intensive sectors declines over the course of the 21st century, there will be an impact on energy intensity independent of the rate of improvement in energy efficiency. The 21st century should witness an increasing fraction of all nations moving through the industrial age to a "post industrial age" in which the service sector looms relatively large. Since the energy intensity of services and related activities is lower than that of many industries in the manufacturing sector, annual energy intensity will tend, on this account, to decline. We try to account for the way in which long term sectoral changes in economic activity may affect the rate of decline in energy intensity. To do so, we use sensitivity analysis to examine a range of potential impacts that sectoral changes may have on energy intensity.

Most industrial/commercial economic activity can be grouped into a category described as low to moderate energy intensity relative to a few industries that have high energy intensity. The high energy intensity industries consist mainly of the utility and transportation sectors (already accounted for above) and about five broad industrial groups within the manufacturing sector, i.e., pulp and paper, iron and steel, non-ferrous metals (e.g., aluminum, copper, magnesium, etc.), non-metallic minerals (e.g., cement, glass, etc.), and chemicals and petrochemicals**(31)**. The highly energy intensive industry groups have an average energy intensity about an order of magnitude higher than the energy intensity of the rest of the manufacturing sector. It should be noted that economic activity in these highly energy intensive industries is cyclical, expanding rapidly in booms and declining sharply in recessions. This can make calculated energy intensities quite variable over short periods of time.

In Table 8 column B, we present the relative shares of high and low intensity industries in the industrial sector. The ratio of one third to two thirds is based on the proportion of high intensity industries from U.S. Census Bureau NAICS 31-33: Manufacturing**(32)**. The high intensity industries are the five highest energy intensity industries in Table 1 of Miketa (2000)**(31)**. The ratio of the energy intensity of high intensity industries to that of the lower ones in column C, i.e., 10:1, was also estimated from Table 1 of Miketa. Column D is an index obtained by multiplying column B by column C. In column F, it is assumed that the ratio of the energy intensity of high intensity industries to that of the lower ones i.e., 10:1, is the same in 2100 as it was in 1990.

We can estimate the annual average energy intensity decline for the changes from high to low energy intensity industries from the indices in columns D and G of Table 8. A decline in the index from 4.0 to 1.9 over 110 years is 0.67% annually. Industrial output, not including electricity and transportation service, contributes only one third of world GDP, 34% in 1990**(33)**, which is consistent with the portion of world energy on Table 4 of about 31% consumed by industrial activities, i.e., 0.43% x ((50%(Ind.) + 22%(Comm.)) = 31%.

**Table 8. The effect of increasing the Gross Domestic Product (GDP) contribution of low energy intensive industries in the Industrial Sector**

| A | B<br>Estimated portion of industrial GDP in 1990 % | C<br>Relative energy intensity index in 1990 | D<br>Index of industrial use energy 1990 (B x C) | E<br>Estimated portion of industrial GDP in 2100 % | F<br>Relative energy intensity index in 2100 | G<br>Index of industrial use energy 2100 (E x F) |
|---|---|---|---|---|---|---|
| High energy intensive industries | 33.3 | 10 | 3.33 | 10 | 10 | 1 |
| Low energy intensive industries | 66.7 | 1 | 0.67 | 90 | 1 | 0.9 |
| Totals | 100 | - | 4 | 100 | - | 1.9 |

Thus, from Table 8 we divide the 0.67% average annual rate of decline by 3 which yields 0.22% average annual energy intensity decline. We add the 0.22% average annual rate of decline due to sectoral shifts to the average annual energy intensity decline due to energy efficiency improvements of 0.83% (see Table 7) for a total of 1.05%. Table 8 is the base case from which the four cases for sensitivity analyses in Table 9 were developed.

**Table 9. Sensitivity to the ratio of high to low intensity industries in 1990 and 2100.**

| | Case 1 | | Case 2 | | Case 3 | | Case 4 | |
|---|---|---|---|---|---|---|---|---|
| | Indust. GDP in 1990 % | Indust. GDP in 2100 % | Indust. GDP in 1990 % | Indust. GDP in 2100 % | Indust GDP in 1990 % | Indust. GDP in 2100 % | Indust. GDP in 1990 % | Indust. GDP in 2100 % |
| (1) High energy intensive industries | 33 | 15 | 33 | 5 | 25 | 10 | 40 | 10 |
| (2) Low energy intensive industries | 67 | 85 | 67 | 95 | 75 | 90 | 60 | 90 |
| (3) Average energy intensity decline | - | 0.16 | - | 0.30 | - | 0.16 | - | 0.26 |
| (4) Average energy intensity decline from energy efficiency | - | 0.83 | - | 0.83 | - | 0.83 | - | 0.83 |
| (5) Estimated total average annual energy intensity decline | - | 0.99 | - | 1.13 | - | 0.99 | - | 1.09 |

The four cases in Table 9 provide a range of average annual energy intensity declines due to sectoral shifts ranging from 0.16% to 0.30 (Row 3). When we combine the sectoral change effects (Row 3) with the overall average annual intensity decline attributable to improvements in energy efficiency (Row 4), the range of average annual energy intensity decline is from 0.99% to 1.13% (Row 5).

## Summary and Conclusions

The purpose of this paper is to estimate the maximum average annual rate of energy intensity decline that can reasonably be expected over the 110 year period, 1990 to 2100. We have estimated the maximum annual rate of decline of energy intensity from increases in energy efficiency for the 110 year period from 1990 to 2100 at 0.83%. When the impact of sectoral change is added, the average annual energy intensity decline is between 1.0 and 1.1%.

Whether or not average annual energy intensity declines in the range of 1.0% to 1.1% are actually achieved depends on how successful we are in implementing existing energy efficiency technology and researching, developing and implementing new energy efficiency technology. Improvements in energy efficiency that could yield an average annual energy intensity decline of 0.83% will not come easily. Achieving this target requires a dedicated and consistent effort. The less successful we are in this effort, the more likely the final result is to be to the left of the 1% line in Figure 1. The effect of the sectoral shift from high to low intensity industries may be reduced if the proportions of energy consumed for electricity generation and transportation, both high energy intensity uses, increase from 1990 to 2100.

We believe our estimates of achievable projected energy efficiency improvements represent an important step in reducing the range of expected values for the long term average annual decline in energy intensity in the 21st century. If anything, we have erred on the side of optimism. In any case, our method allows other values to be fitted into the tables and the effect of the changes on the average annual rate of energy intensity decline to be estimated. Our analysis may also provide some insight into ways of increasing energy efficiency that might exceed our estimates.

We have built on the work of Hoffert et al., which we believe is the most important article about the relationship between energy and stabilization of climate that has appeared in recent years. Our paper attempts to remove much of the uncertainty surrounding the amount of carbon-free energy required to stabilize $CO_2$ emissions at 550 ppmv in 2100. Given the population and GDP growth rate assumptions employed by Hoffert et al., the 37 TW (1188 EJ) they calculated by assuming a 1% annual average energy intensity decline for 110 years is a reasonable estimate of what will be needed.

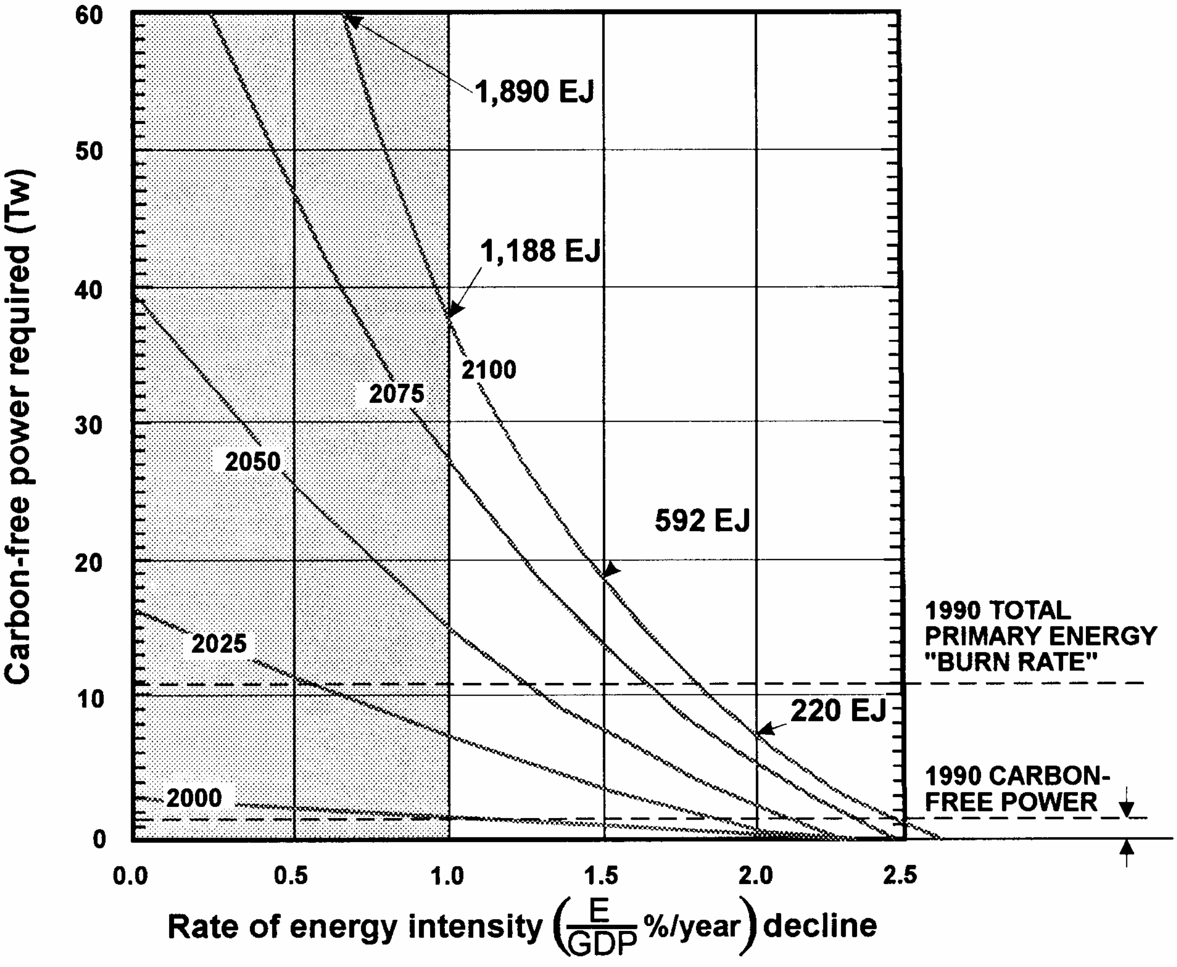

**Figure 1. Carbon-free power vs rate of energy intensity decline**

The shaded area is the estimated probable range of world average annual energy intensity declines from 1990 to 2100. It is superimposed on Hoffert et al.[1], Figure 3, Twenty-first century trade-offs, between carbon-free power required and "energy efficiency", to stabilize atmospheric carbon at twice the pre-industrial $CO_2$ concentration.

## References and Notes:

1. Hoffert, Martin I., et al., 1998, Energy implications of future stabilization of atmospheric $CO_2$ content, Nature, Vol. 395, 29 October 1998, pages 881-884.

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   1 EJ = 1 Exajoule = $10^{18}$ joules: 1 Quad = 1.055 EJ.

3. Ditto Reference 1, page 884.

4. Mechanical Engineer’s Handbook, edited by Lionel S. Marks, Fifth edition, 1951 pages 1105 and 1980.

5. "Carbon dioxide emissions from the generation of electric power in the United States", July 2000, Department of Energy, Washington DC 20585, Environmental Protection Agency, Washington DC 20460, page 8.

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7. Cordesman, Anthony H., 1999, Strategic Energy Initiative, Centre for Strategic and International Studies, World Energy Trends: An Overview,
   Page 1: Rising World Energy Demand: 1970-2015;
   Page 17: The Changing Impact of Electricity by Region Through 2020.
   Page 18: World Electricity Generation by Source of Fuel through 2020.
   Page 19: World Energy Consumption for Electricity Generation by Fuel: 1995-2020.

   (Adapted by Anthony B. Cordesman from IEA, World Energy Outlook, IEA/OECD, 1998, pp. 64-65.)

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    Web site:
    http://discport2b.law.utah.edu/cdroms/Energy/cd_rom/apps/kyoto/enduse2.htm

16. Power to deliver at last?, C&I magazine, Fuel Cells.

    Web site: http://ci.mond.org/9621/962107.html

17. T. Nejat Veziroglu, President, International Association for Hydrogen Energy. "Siemens-Westinghouse is offering solid oxide fuel cells for electricity generation with efficiencies of 70%. PEM and other fuel cells are being prepared for in-house electricity and heat generation with overall efficiencies of 85%." Page 2 of 14th World Hydrogen Energy Conference, June 9th - 14th, 2001, Montreal Canada.

    Web site: www.hydrogen2002.com.

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    Web site: http://www.science.org.au/nova/023/023box01.htm

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Figure 87 Transportation energy consumption in North America and the rest of the world, 1990 - 2020.

World transportation energy in 1995 was about 34 Million Barrels Oil Equivalent per Day, or about 73 EJ, which was about 19% of world energy consumption in 1995.

Web sites: http://www.eia.doe.gov/oiaf/ieo/pdf/transportation.pdf

http://www.eia.doe.gov/oiaf/ieo/images/figure_87.jpg

20. Report # EIA/DOE-0573(99), Carbon Dioxide Emissions.

Web site: http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

21. Climate Change 2001, Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC WG III makes no attempt to estimate the overall improvement in energy efficiency for passenger cars, light trucks, heavy trucks, ships or aircraft. They do, however, provide some useful information about efficiencies.

Passenger cars: “Testing of the Toyota Prius in Japan, Ishitani et al., (2000) found that the hybrid electric design gave 40% - 50% better fuel economy at average speeds above 40 km/h, 70% - 90% better in city driving at average speeds between 15 and 30 km/h and 100% - 140% better fuel economy under highly congested conditions with average speeds below 10 km/h. Actual efficiency improvements achieved by hybrids will depend on both design of the vehicle and the driving conditions. Much of the efficiency benefits of hybrids is lost on long-distance, constant high speed driving”. (Page 194)

Heavy trucks: “Modern heavy trucks are equipped with turbo-charged direct injection diesel engines. The best of these engines achieve 45% thermal efficiency, versus 24% for spark-ignited gasoline engines (Interlaboratory Working Group, 1997)”. (Page 198)

Ships: “Modern marine diesel engines are capable of average operating efficiencies of 42% from fuel to propeller, making them already one of the most efficient propulsion systems”. (Page 198)

Aircraft: From Table 3.11 “Historical and future improvements in new production aircraft energy efficiency (%)” (Lewis and Niedzweicki, 1999). From 1997 to 2050 the estimated increase in energy efficiency is 25% for airframe and 20% for propulsion systems for a total of 45%. This is a reduction in energy intensity of 31%: energy intensity in 2050 would be 69% of that in 1997. (Page 198)

22. Table 1.10 Motor Vehicle Mileage, Fuel Consumption, and Fuel Rates.

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26. DOE/EIA-0632 (97), "A look at residential energy consumption in 1999", November 1999, Energy Information Administration, Office of Energy Markets and End Use, U.S. Department of Energy, Washington, DC 20585.

    Data from Tables 2.7 and 3.1. The amount for “Other appliances” in Table 4 was adjusted from 11.6% to 10.6% to make the total come out to 100.0%. The total in Figure 2.7 of DOE/EIA-0632 (97) adds to 101% due to rounding.

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27. Severns, William H. and Fellows, Julian R., “Heating, Ventilating and Air Conditioning Fundamentals”, Second edition, September 1950, pages 158 and 159.

28. Rosenfeld, Arthur H., et al., Technologies to Reduce Carbon Dioxide Emissions In The Next Decade, Physics Today, November 2000, pp. 29-34. Refrigerators, page 31.

29. Energy Use, Chemical Industry Analysis Brief, Heat and Power Consumption by End Use - 1994.

    Web site:http://www.eia.doe.gov/emeu/mecs/iab/chemicals/page2b.html

30. For purposes of this analysis we have used the same time period of 110 years as Hoffert et al., i.e., 1990 to 2100. Some of the data we have used is from 1990, 1994, 1995 and 1997 because we tried to use the most detailed and complete sets of data. We do not think our conclusions have been compromised by the different dates on the data. If we were to use only 100 years, say from 2000 to 2100, the

average annual rate of energy intensity decline from energy efficiency improvement would be 0.91% rather than 0.83%. The range including sectoral changes would be 1.08% to 1.24% instead of 0.99% to 1.13% as shown in Table 9.

If world energy consumption grew by only three times from 1990 to 2100 instead of four times, then depending on the mix of energy used for electricity generation, the annual energy efficiency improvement might change from 0.83% annually to 0.84%.

31. Miketa, A., "An analysis of energy intensity developments in manufacturing sectors in industrialized and developing countries", Energy Policy 29 (2001) 769-775, Table 1.

32. U.S. Census Bureau, 1997 Economic Census: Bridge between NAICS and SIC: Menu of NAICS Sectors, NAICS 31-33: Manufacturing.

    Web site: http://www.census.gov/epcd/ec97brdg/INDXNA13.HTM

33. 2001 World Development Indicators, 4.2 Structure of output, page 200.

## About the authors:

### H. Douglas Lightfoot

Retired Mechanical Engineer, graduated from UBC in Applied Science in 1952, and received an MBA from Concordia University in 1976. He spent eighteen years with Domtar Inc. at the Research Centre at Senneville, Quebec, where he did research, engineering and economic studies of alternate energies as well as a wide variety of projects for the pulp and paper, chemicals and construction materials businesses of Domtar. Prior to moving to Domtar, he spent five years designing, building and starting up chemical plants at Dupont of Canada, and 12 years of project engineering at Standard Chemical Limited. He is a retired member of the Order of Engineers of Quebec and the Professional Engineers of Ontario, and a Life Member of the American Society of Mechanical Engineers. He continues to have an active interest in energy and energy related subjects and is on the board of the Centre for Climate and Global Change Research at McGill University.

8 Watterson
Baie d'Urfe, Quebec, Canada H9X 3C2

Tel: 514-457-5637
email: dlightfo@aei.ca

### Christopher Green

Professor of Economics, Department of Economics, McGill University. He has been at McGill since 1969 (32 years). He received his PhD from the University of Wisconsin in 1966. Before turning to the Economics of Climate Change, his main research and teaching field was Industrial Organization. He began research on the economics of climate change in 1988, and began teaching a course on the subject in 1994. He has been a member of the Centre for Climate and Global Change Research at McGill University since its inception in 1990.

Department of Economics
McGill University
805 Sherbrooke Street West
Montreal, Quebec, Canada H3A 2T7

Tel: 514-398-4830
email: chris.green@mcgill.