Climate change is an energy problem

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Abstract

A knowledge of the quantity of energy the world uses annually, how it is used and the effect it has on the well-being of humans is important to understanding the impact of proposed solutions to global warming. There are no substitutes for fossil fuels on the scale needed and there is nothing in sight. This report discusses the limitations of conservation, energy efficiency and renewable energies and suggests a course of action to limit the level of carbon dioxide in the atmosphere to 550 ppmv, twice that of pre-industrial days, by 2100.

Slide 1. Climate change is an energy problem.

This paper is part of the McGill Centre for Climate and Global Research report No. 2001-1 by the same title. The reference numbers have been retained from the original report, and a list of the references is available to those who wish to have one.

Slide 2. Historic levels of carbon dioxide (CO_2) in the earth's atmosphere.

The horizontal scale on the left side of this chart covers 500,000 years before the current era (BCE) and on the right side it covers 500 years. The vertical scale representing carbon dioxide (CO_2) levels in the earth's atmosphere is the same for both sides of the chart.

The left side is a 400,000 year record of CO_2 in the earth's atmosphere as measured from the Vostok Ice Cores(1) in Antarctica. The range of values remained between about 170 ppmv and 300 ppmv (parts per million by volume) for 400,000 years. There is a break between the two horizontal scales which is about 2000 years during which the level of CO_2 in the atmosphere was relatively constant between 270 ppmv and 280 ppmv. The right hand scale is the record from about 1700 to the present day. The data up to 1953 are from the Siple Ice Cores(2) in Antarctica. There is a slight break in the data and from 1959 to the present, the data are from direct measurements of CO_2 in the atmosphere taken at Mauna Loa in Hawaii(3).

During the 1800s, sufficient amounts of fossil fuels were being burned that the level of CO_2 in the atmosphere began to rise. In the next 150 years the atmospheric concentration of CO_2 rose above the pre-industrial level of 270 ppmv to 280 ppmv to about 368 ppmv in 1999. The actual range for 1999 was a high of 371.2 ppmv at the end of the winter, and a low of 364.7 ppmv at the end of the summer. The latter is the result of plants in the northern hemisphere removing CO_2 from the atmosphere by photosynthesis in the summer and storing it as biomass. During the winter, the biomass decays or is eaten and fossil fuels are burned and the level of CO_2 increases.

Point B represents an estimate of when the CO_2 level in the atmosphere will reach 550 ppmv based on the Intergovernmental Panel on Climate Change (IPCC) "Business as Usual" scenario IS1992a[(5)]. Point K, calculated by James A. Edmonds[(5)], represents the estimated rise in CO_2 levels if all of the developed countries that signed at Kyoto (Annex 1 countries) were to meet and maintain their commitments. Meeting this commitment would delay reaching 550 ppmv by about ten years. The level of CO_2 would continue to rise at about 1-1/2 ppmv per year, and carbon emissions would rise from the more than half of the world's population that has not signed onto Kyoto.

The WRE 550[(6)] line represents what might be a reasonable path to a target concentration of CO_2 in the atmosphere of 550 ppmv. This report discusses how we might achieve this target.

Without the greenhouse effect of CO_2, the major greenhouse gas, and other minor gases, the atmospheric temperature would be -18°C[(4)] and the earth would be a frozen planet. Carbon dioxide concentration in the atmosphere and the average atmospheric temperature move together. The troughs in the Vostok Ice Core record of about 180 ppmv of CO_2 are ice ages, and the peaks of about 270 ppmv are when the ice melted. By 1900 the level of CO_2 had reached about 295 ppmv, and by the end of the twentieth century had reached 368 ppmv. With this increase of 25% in the CO_2 concentration of the atmosphere over the last two centuries one would expect to find a measurable increase in the earth's average atmospheric temperature.

Slide 3. Global average near-surface temperatures, annual anomalies, 1860-1999[(7)].

The temperature record confirms a measurable increase of about 0.6°C in the earth's average atmospheric temperature since the late 19th century when the atmospheric concentration of CO_2 was about 295 ppmv. The rise in temperature is not smooth and continuous like that of the rise of CO_2 in the atmosphere because several natural and man-made factors temporarily override the influence of CO_2 on atmospheric temperature.

Water vapour has an effect in the form of clouds which can both reflect sunlight (-) and retain heat (+) in the earth's atmosphere. Radiation received by the earth from the sun varies according to variations in the sun's energy output and the distance the earth is from the sun. Dust from volcanic eruptions lowers the atmospheric temperature by reflecting the sun's rays away from the earth. For example, the dip in atmospheric temperature after 1991 was caused by dust from the eruption of Mount Pinatubo on June 15, 1991. The effect of methane, the second most important greenhouse gas, is small in comparison to that of CO_2, and about half comes as "swamp gas" from wetlands.

By far, the largest of the anthropogenic sources of atmospheric carbon is CO_2, and to a much less extent methane, from the production and use of fossil fuels. Methane is also released by several human activities, such as farming of ruminant animals where part of their digestion is a fermentation process that releases methane. Burning of biomass at too low a temperature releases methane. The use of Freon is being phased out by the Montreal Protocol because alternatives are available. Sulfur aerosols are discharged to the atmosphere when fossil fuels are burned and they reflect sunlight. Nitrogen oxides from the burning of fossil fuels have a smaller effect than methane.

It appears that human activities have measurably raised the temperature of the earth's atmosphere above that of pre-industrial days by introducing greenhouse gases into the atmosphere, chiefly CO_2 from burning fossil fuels.

Slide 4. Energy options and climate change - two scenarios

Not everyone looks at climate change and energy in the same way. For example, here are two very different views:

1. The best known scenario is a view held by many people including scientists, environmentalists, politicians, and the general public. Their view is that the energy problems affecting climate change can be solved by *"Conservation, increases in energy efficiency and the extensive use of renewable energies."*

The terms "increase in energy efficiency" and "energy intensity decline" mean the same. "Energy efficiency" is known by almost everyone, whereas "energy intensity", which is the amount of energy per unit of output, is used by economists. Both terms will be used in this report.

Conservation is defined as changes in the personal choice an individual can make to save energy related to comfort, convenience, security, safety, likes and dislikes, life style, etc. These choices are wide ranging, variable over time, unpredictable, difficult to classify between necessary and unnecessary, and a small contribution to what is needed.

Increases in energy efficiency are important and depend on technology, which becomes more difficult to find and implement as the limit of energy efficiency is approached.

The extent of the use of renewables depends on the availability of land.

2. Lightfoot and Green, and Hoffert et al. state that the problem cannot be solved simply by #1. In their view *"The impact of conservation is limited and relatively small,*

increases in energy efficiency are limited and renewables need too much land to supply more than a fraction of global energy requirements. New, large sources of carbon-free energy are needed to replace fossil fuels."

This view was reached after examining how much energy the world uses, how it is used, how much might be needed in the future, how much carbon-free energy would be needed to stabilize the level of CO_2 in the atmosphere, the contribution from energy efficiency and the supply of carbon-free energy from presently known energy sources.

Slide 5. How Canada uses energy.

It is necessary from here on to talk about quantities of energy to provide a rational look at the problems and possible solutions. The unit of energy used throughout this report is the "Exajoule", or EJ. One EJ is equal to 10^{18} joules, and is about 5% smaller than One Quad, which is 10^{15} British Thermal Units or one quadrillion BTUs. In amounts of fossil fuels, 1 EJ is the amount of energy in the petroleum contained in 105 super tankers the size of the Exxon Valdez, or approximately 28 billion litres of gasoline.

In 1997, Canada used 10.2 EJ[(8)] of energy in all forms. During the same year, the United States used 99.4 EJ[(9)] and world consumption was 400.8 EJ[(10)].

If we examine the CO_2 emissions of Canada[(8a)] and the United States[(11)] we can see some similarities and some differences. Canada uses about the same percentage of energy consumption for transportation, but the US uses a larger percentage to generate electricity. Gasoline, which is used by cars and light trucks, is 60% of the transportation fuel in the US[(11)], or about 20% of total energy use. In other words, cars and light trucks are about one fifth of the carbon dioxide emissions problem in North America and less than 10% in the world. Most of the remaining transportation fuel is diesel fuel (20%) for heavy trucks, trains, and ships and jet fuel (13%) for aircraft.

If cars and light trucks in Canada consume the same proportion of transportation energy as in the US, a not unreasonable assumption, then they account for about 20% of carbon dioxide emissions, or the same as that for generating electricity. In the US, generation of electricity emits about twice the amount of carbon dioxide annually as cars and light trucks.

Canada produces a greater proportion of electricity by hydro than the US or the world, much less by fossil fuels and about the same percentage by nuclear fission. Ontario accounts for about one half of the nuclear fission generated electricity in Canada and New Brunswick about one third.

Canada uses significantly more electricity per capita than the US or the world. The world uses only about 2 MWh per capita because about 40% of the world population is not connected to an electricity grid.

It is difficult to compare Industrial, Residential and Commercial energy use between Canada and the US. In the lower part of Table 5.1, each of these items under US contains some portion of electricity generation, and it is not easy to find out how much is, or is not, included in each.

Slide 6. World energy consumption.

World energy consumption by fuel type was 204.2 EJ in 1970 and 385.7 EJ in 1995. Energy consumption has grown 77% in 25 years and all sectors have grown.
The percentage of fossil fuels i.e., coal, oil and natural gas, in this period has dropped by about 8 percentage points in 25 years, from 93.7% to 85.4%, mainly because of the growth in nuclear fission and hydro, both carbon-free energies.

About 27% of the 329.3 EJ of fossil fuel used in 1995 was for the production of electricity.

Slide 7. History and projections of world energy consumption.

All of the information on this slide, except for the Energy Information Administration (EIA) material, is from an article by Hoffert et al. in **Nature**, October 29, 1998[6]. The energy values in the article have been converted from terrawatts (TW) to exajoules (EJ) using a conversion factor of 1 TW yr = 31.5 EJ.

Historic world energy consumption is shown from 1970 to 1995. A projection made by the Energy Information Administration (EIA) to 2020, and the IPCC IS92a "business as usual" case from 1990 to 2100 are also shown for purposes of comparison. The Intergovernmental Panel on Climate Change is a group of scientists from around the world who are studying all of the factors associated with global warming. IPCC Working Group I projected IS92a.

World energy consumption was about 347 EJ in 1990, of which 47 EJ was carbon-free energy. From IPPC projections, energy consumption doubles to about 700 EJ by 2025, triples to about 1,050 EJ by 2060 and quadruples to about 1,400 EJ by 2095.

Energy consumption is increasing because there is a strong positive correlation between income per capita and energy consumption. The next slide, Slide 9, shows this correlation. Throughout the world, most people are striving for a higher income. From 1890 to 1990 the rate of increase was 1.6%, and it is expected that this rate will be maintained for the next hundred years.

Energy consumption is also increasing because population is increasing. The rate of population increase averaged 1.3% annually between 1890 and 1990. The projections by Hoffert et al. are based on the UN mid-range projection made at the time the IPCC IS92 scenarios were developed[6]. It forecasts a changing rate of population growth from 1.6% in 1990 to 0% in 2100, when world population is estimated to level out at 11.3 billion. Hoffert et al. used an average percent rate of change of population of +1.3% to 2025 and an average of +0.7% from 2025 to 2100.

The IPCC projection IS92a and the WRE 550 scenario both have built-in an energy intensity decline, or energy efficiency increase, of 1% per year.

WRE 550 is just one of several paths of emissions reduction to stabilization of CO_2 in the atmosphere prepared by Wigley, Richels and Edmonds (WRE), **Nature**, October 29, 1998[6]. They looked at several paths and concluded that we must choose the least cost path. WRE 550 is of special interest because limiting the concentration of CO_2 in the atmosphere to 550 ppmv by 2100 might be a reasonable target, about twice the level of the 270 ppmv of the pre-industrial era, and about 50% higher than the current 368 ppmv. This particular path starts slowly, thereby allowing time for technology to provide the carbon-free energy and energy intensity reductions necessary.

In about 2035, the world will need about 350 EJ of carbon-free energy, which is about the same as total energy consumption in 1990, will double to about 700 EJ by about 2065 and triple to about 1,050 EJ by about 2090. Note that to achieve 1100 EJ of carbon-free energy annually by 2100 we need to add an average of about 10 EJ of new carbon-free energy each year to 2100. These are very large amounts of carbon-free energy and raise the question of where it is going to come from.

The IPCC IS92a projection and the curve of carbon-free energy do not meet in 2100. There is a gap of about 300 EJ. There is some controversy as to the actual size of an acceptable gap because it depends on how much CO_2 is absorbed by the oceans and by the terrasphere. Based on present atmospheric temperatures and CO_2 concentration, one estimate predicts that CO_2 emissions have to be reduced by 60% to 70% from present levels, to stabilize atmospheric CO_2 levels.

Slide 8. Per capita income versus energy consumption.[19]

There is a strong positive correlation between the Per capita mean GDP (GDP/N), i.e., Gross Domestic Product, or income per capita and Per capita mean power consumption (E/N).

The vertical and horizontal scales on this graph are logarithmic scales. Thus, the people living in the countries shown in the upper right corner use about one hundred times more energy and have about one hundred times the income of those who live in the countries shown in the lower left corner.

On average, most people in the world are trying to move up the slope towards higher income. This, and the fact that most of the world's population live in countries shown on the lower left side of the chart explains why the Gross Domestic Product per capita (GDP/N) is expected to grow throughout this century by +1.6% annually.

It appears that even if the population growth rate levels off sooner than expected, there will still be significant pressure to increase income per capita, thereby increasing energy consumption. The importance of energy to the well being of the world's people cannot be overemphasized.

Slide 9. Per capita mean GDP, or income, and conservation.

The amount of GDP per capita or income per capita is represented by all of goods and services we consume. Examples of these are fresh fruits and vegetables all year, preserved foods, meats, dairy nutritional supplements, medicines, drugs, and other health products. This is only a start on the list - many more are listed on Slide 9, but the list is very long. It becomes very clear that energy is vital to our everyday lives.

As we look closely at the items making up income per person, it becomes clear that conservation and changes in human behaviour are a relatively small part. In addition, there is no widespread agreement on what constitutes conservation, or acceptable changes in human behaviour. For example, "No one needs a dog!", would be popular in some circles and be very upsetting to people who value them as "part of their family". Everyone should walk of ride a bicycle! In the winter in Canada? How about those who cannot ride a bicycle for whatever reason and those people who prefer to live in specific areas far from their work? Turn out all lights when not in use! Lighting is used for safety and security. No one needs a van or SUV! If that is the case, what are the reasons they are so popular. Are these reasons valid? What do the owners of the vans and SUVs say?

Conservation and changing human behaviour is not a solution. Each of us can make a small contribution by practicing conservation in our own way.

Slide 10. Sensitivity to energy intensity decline using the Kaya equation.

Using the Kaya equation and the WRE 550 scenario, Hoffert et al. prepared this chart to show the relationship between the percent annual rate of decline in energy intensity versus the amount of carbon-free energy needed to stabilize the level of CO_2 in the atmosphere at 550 ppmv.

The WRE 550 curve of carbon-free energy required to limit levels of CO_2 in the atmosphere to 550 ppmv (Slide 8) was based on an annual rate of energy intensity decline of 1.0%. That is the vertical line at 1.0 along the bottom of the chart.

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 to 1%, the rate employed by Hoffert et al (1998), reduces the carbon-free energy requirement to about 37 TW (1188 EJ/yr). A further increase to 2% reduces carbon-free energy requirement to about 7 TW (220 EJ/yr).

This history of energy intensity decline is too short to use as a basis for making a reliable estimate of future rates of decline. This, together with the fact that declines in the rate of energy intensity have to "bottom out" somewhere, suggests a slightly different approach to the problem.

Slide 11. Land to produce 1 EJ of energy per year from renewables.

Fossil fuels: Fossil fuels are concentrated solar energy, whereas renewable energies are often dilute and variable. The output of three 150,000 bpd oil refineries is approximately 1 EJ.

Hydroelectric power: Hydro power comes from water which is recycled by solar energy in the form of rain or snow which falls over large areas. Nature concentrates the water into rivers and lakes. Dams can be built to store the water and use its energy when needed. Hydro power is the most widely used of the renewable energies because it is concentrated naturally and it can be stored.

James Bay will occupy an estimated 19,300 sq. km/EJ of installed capacity when completed. Total installed capacity will be 0.8 EJ, and delivered electricity will be about 0.5 EJ. Capacity factor is 50% to 60% of the installed capacity because installed capacity is only needed at peak periods.

World installed hydroelectric generating capacity in 1995 was about 22 EJ. The amount of electricity produced at 60% capacity factor would be about 13 EJ. To produce 13 EJ of electricity in a fossil fuel powered generating station would require about 40 EJ of fossil fuel. Thus, hydroelectric power is already displacing about 40 EJ of fossil fuels. Development of all of the world's remaining hydropower by 2020 would yield an additional about 13.8 Exajoules of electricity delivered to customers, and displace another 40 EJ of fossil fuels. Installation of 75% of remaining capacity would generate an additional 10 EJ of electricity annually, or one year out of the 110 years.

Biomass fuel: Trees are preferred for the growing of biomass for energy generation because trees can accumulate and store solar energy for several years before harvesting, thereby minimizing the energy for collection and processing. If heat is required, burning of biomass directly is the most efficient use of biomass.

Forests are already well used. There is not much spare capacity. Wood already is a significant source of energy for paper mills, other than newsprint mills. Wood is chemically treated to recover about one-half of the wood as cellulose for making paper. The remainder is lignin and other organics which are burned in a recovery furnace to provide heat for the paper-making process and to recover the chemicals for recycling.

At an average yield of 32,000 sq. km per EJ, conversion of all world crop lands to biomass production for fuel would produce about 460 EJ, a bit more than present world energy consumption. Using 2% of the world's agricultural crop land would produce 10 EJ of solid biomass fuel, or 1 year out of 110 years.

Methanol: Conversion of wood into methanol takes energy, more than there is in the final methanol. Thus, the area per EJ for methanol production is more than twice that for solid biomass. However, liquid methanol is more readily transported world wide and can be used in most energy applications, whereas the usefulness of solid biomass is limited. Using 5% of the world's crop land for methanol production would produce 10 EJ of energy, or one year out of 110 years.

Ethanol: The land for growing of sugar cane for any purpose is limited by the amount of suitable land available in a suitable climate. This example is here because sugar cane is an agricultural crop with one of the highest rates of converting solar energy into biomass, i.e., approximately 1.2% versus, for example, soya beans at 0.16% and cassava at 0.8%[(23)]. Cassava is a tropical plant with starchy roots from which tapioca is made.

Wind: Wind is a dilute and intermittent form of solar energy. Because of its intermittent nature, wind works best when supplying up to about 20% of the electricity output of an electrical grid with a continuous base load source of fossil fuel, nuclear energy or hydro. The generating capacity of the base load system has to be sufficient to supply the peak demand without wind power.

Wind power requires about 20,000 sq. km per EJ[(12)]. The area dedicated for towers, electrical equipment and roads is about 5% of the total area, or about 1,000 sq. km. The remainder can almost always maintain its existing use, such as farming or ranching. Wind turbines need to be spaced apart roughly ten times the diameter of their rotors to avoid uneven wind flow between machines, lower efficiency and increased stress on the units. Wind sources are usually far from where energy is needed. For example, the twelve Great Plains states are the windiest region of the US, and are far from the major electricity consuming areas.

In 1998, installed wind power capacity was 0.30 EJ world-wide. As the capacity factor for wind is about 25% (23.5% for the US in recent years)[12], the actual amount of electricity delivered was about 0.075 EJ world-wide[26]. This was twice as much as in 1995. The growth rate in this period was approximately 26%, which makes it the fastest growing energy source in the world on a percentage basis.

If wind continues to grow at 26% annually, it would provide 10 EJ of electricity in 2019 and displace about 30 EJ of fossil fuels and provide three years out of 110 years. In 2019, windmills would be installed on 200,000 sq. km, an area equivalent to the distance from Windsor to Quebec City and about 200 km wide, and would be installed on land at the rate of 52,000 sq km annually.

Solar-hydrogen: Solar energy as light is dilute and intermittent so for this analysis it was assumed that hydrogen would be made from the solar electricity produced and then liquefied so the energy could be stored and used as needed.

The estimated area of land of 2,970 sq. Km per 1 EJ of hydrogen produced is based on using 15% efficient single crystal silicon solar cells. At some point, photovoltaic cells with higher efficiencies, possibly up to 20%, may become available but the amount of land would still be limiting. Concentrator cells appear to have efficiencies in the high 20%s, but they require precise tracking, which requires about twice the land area per panel compared to that of flat plate solar panels. The efficiency of solar cells is more important than their cost because efficiency reduces the area needed for a given output. The rate of solar energy recovery is about 4.3% in Tucson (32nd parallel), and about 1.4% in Seattle (48th parallel) because of less solar radiation and a lower sun angle.

Tucson has the highest rate of solar insolation in the United States. The 2,970 sq. Km. needed to produce 1 EJ of hydrogen is about 1% of the 295,260 sq. Km. of Arizona. It may seem like an easy task to find 2,970 sq. Km. for solar cells. However, solar panels require relatively flat land for access of vehicles between the rows for cleaning and other maintenance. The difficulty in finding 2,970 sq. Km. of suitable area becomes clearly evident when one starts to look closely at how to fit this amount of area onto flat or gently south facing land among the towns, cities, roads, railroads, farms, and other land occupied in various ways. Finding enough suitable land for installation of even 1 EJ of solar hydrogen in Arizona is not an easy task.

Production of hydrogen for storage of the energy produced can be accomplished by electrolyzing water into hydrogen and oxygen. Each kilogram of hydrogen requires nine kilograms of water. To make 1 EJ of hydrogen each year and store it in liquid form requires 217,000,000 litres of water per day just for the hydrogen, and it takes 25% of the energy in the hydrogen produced to liquefy the remainder. This amount of water is the same as that required for a city of about 500,000 people. Sufficient water supply is not available in Arizona.

Further, for each kilogram of hydrogen produced, eight kilograms of oxygen are produced as a by-product. Oxygen is a hazardous material and safely disposing of this amount of oxygen is not a trivial problem. Combustion rates are dramatically increased by increasing oxygen concentration in the atmosphere from its present level of 20.8% to, for example, 25.8%. If for some reason a shirt sleeve caught fire at the normal concentration of oxygen, i.e., 20.8%, people could move quickly enough to put it out before serious injury occurred. However, at an oxygen concentration of 25.8%, the whole shirt would be on fire before anyone could move.

Dilution of oxygen to a level much closer to 20.8% is necessary before it leaves the hydrogen production facility, and this requires enormous quantities of dilution air. The problem is further complicated by large production rate peaks for hydrogen and oxygen that occurs between 10 AM and 2 PM on summer days, or about five times the average production rate over a year. For example, at peak periods it takes as much air as there is in a line of Goodyear blimps, like the Spirit of Akron, nose to tail 9,000 kilometres long every hour to dilute the oxygen to 23%.

Suppose photovoltaic cells were placed on the roofs of houses to generate hydrogen. Considering roof orientation, roof shape with dormers, etc., and shade from trees, chimneys, etc., maybe only 50% of the houses are suitable for the installation of 60 square metres of photovoltaic solar cells. On this basis, and a solar insolation rate about the average for the US, it would take about 60,000,000 houses to supply 1 EJ of hydrogen. For North America, the total would be 1 EJ to 2 EJ, excluding apartment buildings.

In 1998, installed photovoltaic cell capacity was approximately 300 MW, or 0.0095 EJ. The actual electricity output would be about 0.002 EJ because the capacity factor is about 20%. If electricity output of 0.002 EJ grows at 26% annually for about 36 years it would provide 10 EJ of electricity, or one year out of 110 years. At the end of 36 years, solar arrays would be installed on about 20,000 sq km of land and 5,200 sq km of land would be added annually.

Slide 12. Renewable energy for 10 EJ, one year out of 110

This table summarizes what it would take for each of the renewables to provide 10 EJ of energy more than now. The amount of fossil fuels that might be displaced is also shown. Renewables currently provide about 7% to 8% of total world energy supply. We think they will continue to contribute in the range of 5% to 10% of world energy supplies to 2100.

Hydro will always be important, and solar and wind energy will always have important small niches.

Slide 13. World electricity supply from nuclear fission is growing.[15]

Nuclear fission energy first delivered electricity in 1955 and grew significantly from 1970 to 1995. It now generates about the same amount of electricity as hydro, which has limited growth potential. There are no technological reasons why, in the future, electricity generated from nuclear fission cannot significantly exceed that produced by hydro power.

In 1995, world electricity production consumed 147.1 EJ, or 38% of world energy consumption to make 42.5 EJ of electricity, i.e., 28.9% efficiency. Electricity powers the world of electronics, lighting and electric motors of all sizes and has so many useful applications that cannot be replaced by other forms of energy, that we accept the large inefficiency of production.

Thus, we should learn to conserve electricity and use it only where there are no alternatives. A house heated with electricity generated by burning fossil fuels emits more than twice as much CO_2 to the atmosphere than burning the fossil fuel directly in a furnace to heat the same house.

It is estimated that two billion of the world's people are still not connected to electric power grids. Thus, electricity generation is expected to grow about 2.5% annually, and reach 60 EJ by 2010.

In 1999, there were 435 nuclear fission plants generating electricity in 30 countries, and 38 new plants were under construction in 13 countries. This represents a 9% increase in installed capacity when the last of these plants is completed and producing electricity in about four years.

To deliver 1 EJ of electricity annually requires 53 nuclear fission plants of 1000 MW capacity operating at 63.5% capacity factor and consuming about 3 EJ of uranium. To supply all the world's energy consumption of 347 EJ in 1990 would have required about 18,000 nuclear fission plants like these.

How long will supplies of uranium last? In the PBS documentary, "What's Up with the Weather", Martin Hoffert of New York University says, "You may have about ten years of U_{235} power from all of the cost effective uranium reserves. Even if you look at reserves which are more expensive now, by this time the nuclear power would be considerably more expensive. You might have thirty or forty years at ten terrawatts. And what if you need 20 or 30 or 40 terrawatts for a hundred years Now you are done."

Ten terrawatts of power, about world energy consumption in 1990, for ten years is equivalent to 3,150 EJ using cost effective reserves. Using all reserves, the total is 9,450 EJ to 12,600 EJ.

At present consumption rates, the cost effective reserves would last for more than one hundred years, and all reserves would last about four hundred to five hundred years. Nuclear power is growing and is likely to continue to do so, thus, uranium reserves may run out sooner than these figures indicate, depending on the growth rate, and the success of exploration for new sources.

Nuclear fission breeder reactors develop more fuel in the form of plutonium than they consume. Thus, there could be nuclear fuel for thousands of years if breeder reactors were used. There are some, but not many, breeder reactors in operation today. There are concerns about the potential dangers in the management of plutonium.

Nuclear fusion: There are several possible routes to nuclear fusion power. Most appear to be long term and the research is expensive, but supplies of the heavy water fuel are virtually unlimited, and there appear to be no long term radioactivity problems. The results may not be certain, but the potential payoff is well worth pursuing.

Slide 14. Hydrogen is not a source of energy.

Hydrogen is not a source of energy. It must be manufactured from other sources of energy. One of the least energy intensive processes is steam reforming of natural gas, a process that discharges CO_2 and requires at least 1.5 units of energy to produce one unit of energy as hydrogen.

If the natural gas is first converted to methanol and the methanol reformed to obtain hydrogen, more energy per unit of hydrogen is required.

The manufacture of 1 EJ of gaseous hydrogen annually by electrolysis of water requires about 37 nuclear fission plants of 1000 MW of electricity capacity at 100% capacity factor and 90% utilization and consuming about 4 EJ of nuclear fuel. If the hydrogen must be liquefied for storage or transportation, then an additional amount of energy equal to about 25% of the energy in the hydrogen is required - add nine more nuclear fission plants for a total of 46 and increase the nuclear fuel consumption to 5 EJ.

The "hydrogen economy" will not come soon or easily. For example, the time for finding 37 sites, obtaining approvals, building 37 nuclear fission plants and bringing them into production is likely measured in decades.

One EJ of hydrogen requires enough water for a city of 500,000 people just for the hydrogen - not including water for cooling, people or other uses. The problem of safe oxygen disposal will be easier to solve than that for solar hydrogen because there are no large peaks of production.

Hydrogen is very light and boils at -253°C (20.38°K). Liquid hydrogen cannot be stored in a simple tank, but requires a vacuum insulated tank.

Although hydrogen has a very high energy to weight ratio, it has a very low energy to volume ratio, both as a liquid and as a gas. For example, a given volume of liquid hydrogen has about one-quarter the energy of the same volume of gasoline.

The "hydrogen economy" will not arrive until there are large supplies of carbon-free energy to produce it, and then it may not arrive, but there will be niches where hydrogen is a good solution.

The relatively high volume density of liquid hydrocarbon fuels makes them the preferred transportation fuel. It might be wise to save our oil solely for transportation and chemical feedstocks until there is a good alternative source of energy available.

Slide 15. Conclusions:

1. Stabilization of CO_2 concentration in the atmosphere is a difficult task. There are no simple or easy solutions.

2. Increases in energy efficiency alone will not stabilize the level of CO_2 in the atmosphere. Energy efficiency increases can only displace about one half to two thirds of the carbon-free energy otherwise needed. However, new energy efficiency technologies are very important and are more advantageous over the long term the earlier they are implemented.

3. Renewable energies cannot replace the base load of energy now carried by fossil fuels. Renewables such as wind and solar are dilute and intermittent - all renewables require very large amounts of land. However, renewables will always have a relatively small, but important role in world energy supply, probably in the range of 5% to 10% of world energy supply and, possibly, declining as world energy consumption rises.

4. The world's population will have to adapt to higher levels of CO_2 in the atmosphere while humankind tries to find energy solutions to limit the level of CO_2 in the atmosphere. Energy is too vital to the well-being of people in our modern society to "just turn off the fossil fuel energy tap".

5. Large sources of carbon-free energy are needed to stabilize the level of carbon dioxide in the atmosphere at 550 ppmv, i.e., between 1,188 EJ and 1,890 EJ annually.

6. Conservation is desirable, but is not solution. It is a small and variable component of the climate stabilization picture.

7. These conclusions are not a "doomsday scenario". They are a "wake up call" that we must start now to find solutions capable of stabilizing the level of CO_2 in the atmosphere, while at the same time respecting the well-being of people and the environment in which they live.

Slide 16. Corollary:

The effort needed to find new energy sources and technologies on the scale needed is far more than can be achieved simply by "getting energy prices right". Regardless of what the price is for fossil fuels, there are no substitutes or technologies available to replace fossil fuels on the scale needed to stabilize the concentration of CO_2 in the atmosphere, and there is nothing in sight.

Artificially raising fossil fuel prices in an attempt to substantially cut fossil fuel use prior to the discovery and development of major new sources of energy and technologies may create severe economic hardships, and may generate vigourous political resistance to dealing with the problem.

Recent demonstrations against higher oil prices in Europe and elsewhere have highlighted the effect that interruptions of the fuel supply can have on ordinary people and on governments. As it is, oil production is deliberately kept low by OPEC to limit the supply and keep the price high.

Slide 17. How can the problem of stabilizing the level of CO_2 in the atmosphere at 550 ppmv be resolved?

The developed world can:

1. Vigorously pursue energy efficiency. The most benefit comes from implementing as much energy efficiency technology as possible as soon as possible. Promote implementation of known energy efficiency technology at home and provide for implementation in less developed countries. Promote research into new energy efficiency technology.

2. Vigorously pursue new large sources of carbon-free energy. Initiate large-scale research programs dedicated to the discovery and development of new, large sources of carbon-free energy that can supply 1,188 EJ to 1,890 EJ in 2100. This is a large scale effort and may be long term. Hoffert et al. suggest that a Manhattan or Apollo type project is needed.

Items #1 and #2 are needed equally as each does a large part of what is needed to stabilize the level of CO_2 in the atmosphere.

3. Ensure an adequate and affordable supply of fossil fuels until sufficient carbon-free energy is available. This is essential to be able to pursue the discovery and implementation of new energy technologies and new sources of carbon-free energy in and effective and efficient manner.

4. Provide sufficient and stable long term funding for these research programs - such as a modest tax on fossil fuel consumption dedicated exclusively to fund energy research.

5. Conservation, at its best, would be far short of being a solution - it is small and variable. It is a small contribution each of us can make in our own way.

There are diverse routes to finding and developing new sources of carbon-free energy and to finding new energy efficiency technology. To achieve the best results, competition world-wide between industrial and other research groups can be promoted to stimulate the generation and development of new ideas.

Slide 1

Climate change is an energy problem

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October 5, 2001

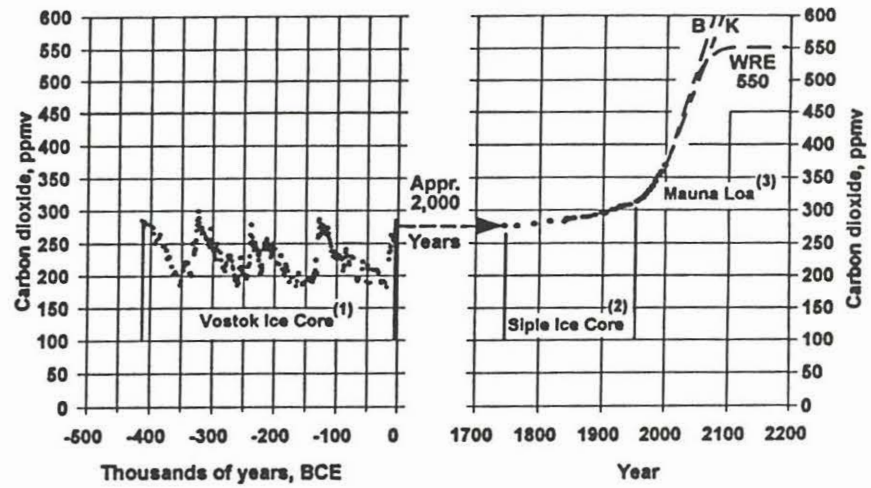
Based on papers written for the McGill Centre for Climate and Global Change Research in 1992 and 2001, and papers written for various journals and symposia.

McGill Centre for Climate and Global Change Research

http://www.mcgill.ca/ccgcr/

Slide 2

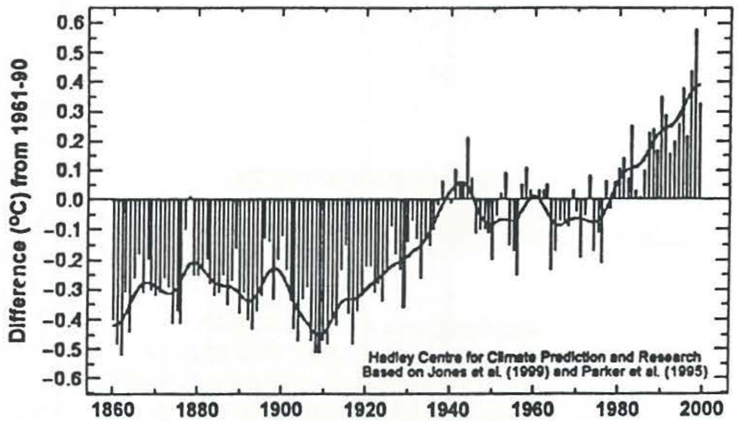
Historic levels of carbon dioxide (CO_2) in the earth's atmosphere



- Without greenhouse gases like carbon dioxide, earth's temperature would be -18°C[4] - no people and no plants.
- Troughs are ice ages, peaks are when the glaciers melted.
- Last few millennia - 270 to 280 ppmv.
- B = "Business as usual", IPCC IS92a.[5]
- K = 6 Gt of carbon emissions Kyoto target extended to 2100.[5]
- WRE 550 = at this point in time, a reasonable target.[6]

Slide 3

Global average near-surface temperatures[7]
annual anomalies, 1860 - 1999



Natural variables:
- carbon dioxide (+)
- water vapour (±)
- variations in radiation from the sun (±)
- volcanoes: dust (-), gases (+)
- methane from wetlands (+)

Man-made variables:
- use of fossil fuels: carbon dioxide & methane (+)
- methane from animals, rice growing, landfills, biomass burning (+)
- chlorofluorocarbons (Freon) (+)
    - phasing out by Montreal Protocol - alternatives available
- sulfur aerosols from burning fossil fuels (-)
- nitrogen oxides from burning fossil fuels (+)

Slide 4

Energy options and climate change - two scenarios

1. The best known scenario. A view held by many scientists, environmentalists, politicians and the public - energy problems affecting climate change can be solved by:

    Conservation, increases in energy efficiency and the extensive use of renewable energies.

2. Lightfoot and Green, Hoffert et al., and a few others state that the problem cannot by solved simply by No. 1. In their view:

    The impact of conservation is limited and relatively small, increases in energy efficiency are limited, renewables need too much land to supply more than a fraction of global energy requirements. New, large sources of carbon-free energy are needed to replace fossil fuels.

Slide 5

How Canada uses energy

Table 5.1	Canada 1997[8]	US 1997[9]	World 1997[10]
Total energy use, EJ	10.2	99.4	400.8

Annual CO_2 emissions	1995[8a]	1995[11]
- Transportation	30%	32%
- Electricity generation	20%	38%
Sub-totals	50%	
- Indust, Resid, Comm, etc.	50%	
Totals	100%	

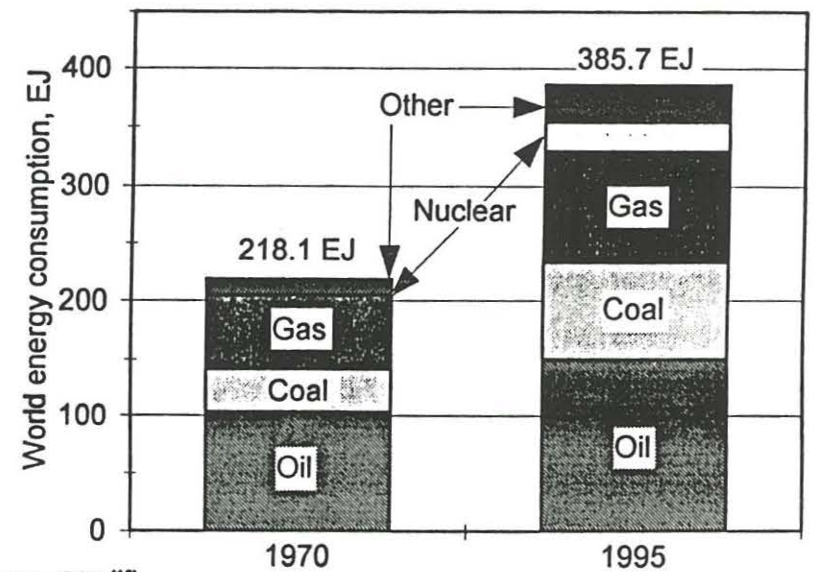
Table 5.2 Electricity Production 1994/95:

	Canada[11a]		US[12]	World[13]
	EJ	%	%	%
Hydro	1.17	61.0	10.0	18.6
Fossil fuel	0.38	20.0	67.0	63.8
Nuclear	0.36	19.0	22.5	17.3
Renewables	-	-	0.2	0.3
Totals	1.92	100.0	99.7	100
MWh/capita (1993)[14]		15.4	11.1	1.95

Slide 6

World energy consumption

Fossil fuels supply 80 - 85% of world energy requirements. Only fossil fuels are currently capable of meeting the world's base load energy requirements.



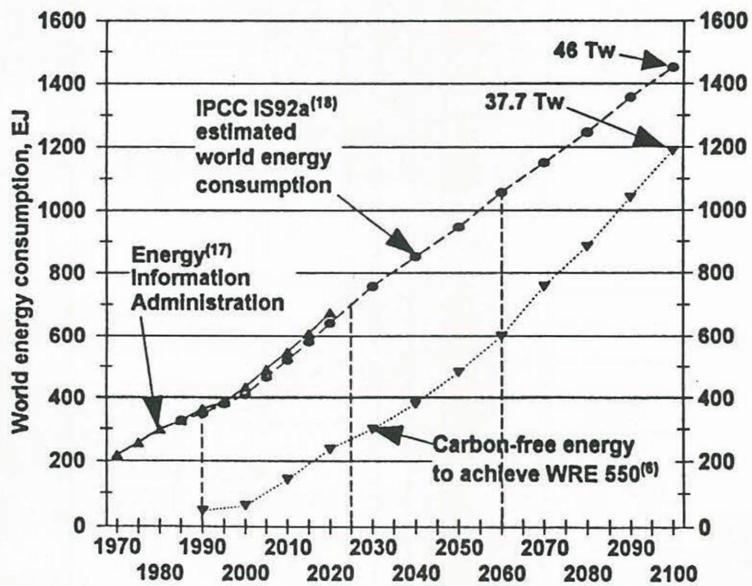
Source: CSIS[15]

	1970		1995	
Fossil fuels	204.2 EJ	93.7%	329.3 EJ	85.4%

Slide 7

History and projections of world energy consumption

- EIA historical record 1970 to 1995, projections to 2020.[17]
- From Hoffert et al.[6]:
  - IPCC projection "business as usual" scenario IS92a
  - Carbon-free energy needed to follow Wigley, Richels, Edmonds (WRE 550) path to stabilize atmospheric CO_2 concentration at 550 ppmv by 2100.



Adapted from Hoffert, et al., 1998[6,18]

Slide 8

Per capita income versus energy consumption[19]

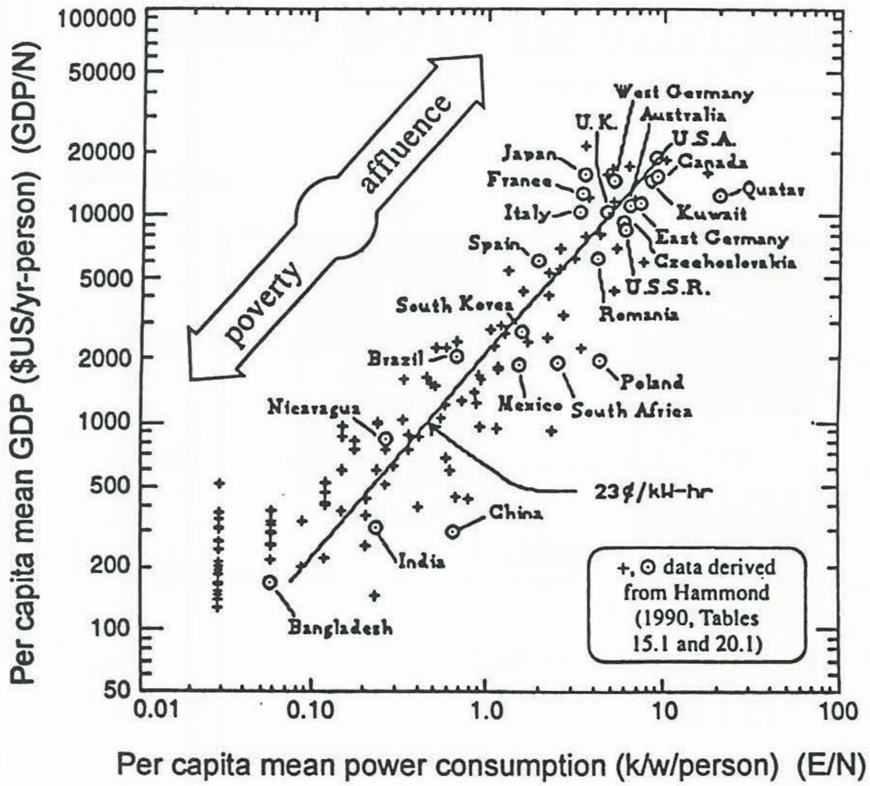


Figure 4.1 Distribution of per capita GDP (GDP/N) vs. per capita raw commercial energy consumption (E/N) for members of the United Nations. Named countries are denoted by circles, unnamed by crosses.

From: Engineering Response to Global Climate Change, Planning a Research and Development Agenda, edited by Robert G. Watts, National Institute for Global Environmental Change, Tulane University, New Orleans, Louisiana, Lewis Publishers, 1997, Chapter 4, Energy Supply, Authors: Martin Hoffert, Seth D. Potter, et al., Figure 4.1, page 214.

Slide 9

Per capita mean GDP, or income, consists of:

Fresh fruits & vegetables all year, preserved foods, meats, dairy, nutritional supplements, medicines, drugs, packaging for health & quality control, other health products.

Roads, bridges, ferry services, airports, harbours, cars, trucks, buses, airplanes, boats, ships, public transit, railroads.

Houses, cottages, apartments, hotels, hospitals, schools, gardens, lawns, parks, green spaces, indoor & outdoor recreational areas.

Stores, shopping centres, factories, office buildings, warehouses, conference centres, public buildings, research centres.

Heating systems, air conditioning, inside & outside lighting, ecalators, elevators, moving walkways.

Pets, bicycles, toys, specialized clothes and shoes, safety equipment, newspapers, TV, movies, videos, magazines, computers, cell phones, FAX machines, cameras, pagers, sports equipment.

The list goes on ...!

Conservation and changes in human behaviour:

A small part of GDP or income per person
- discretionary, often a matter of opinion, controversial.

Examples:

No one needs a pet - dog, cat, etc.!
Everyone should walk or ride a bicycle!
Turn out the lights!
No one needs a van or SUV!

Conservation - it is not a solution, but a small contribution each of us can make in our own way.

Slide 10

Sensitivity to energy intensity decline using the Kaya equation

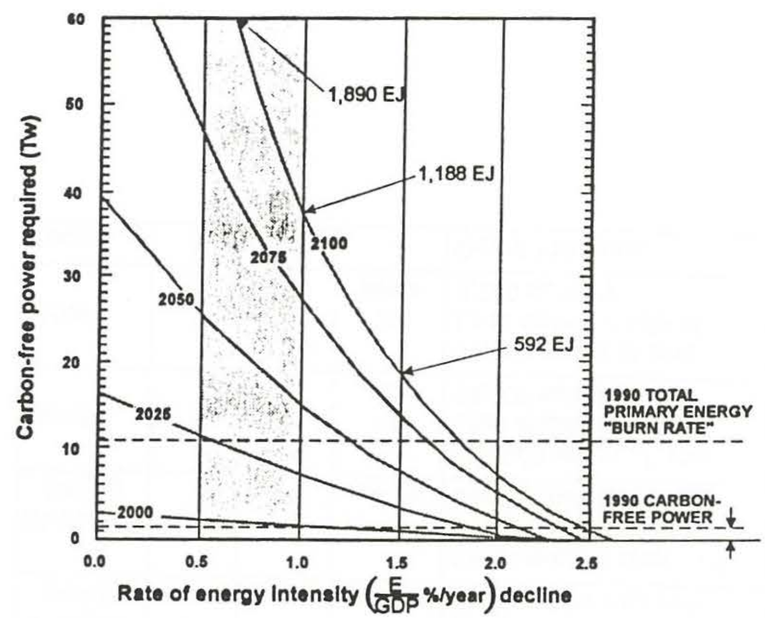


Figure 1 Twenty-first century trade-offs, between carbon-free power required and "energy efficiency", to stabilize atmospheric carbon at twice the pre-industrial CO_2 concentration.

Source: Adapted from Hoffert, et al. (1998)[22]

Slide 11

Land to produce 1 EJ of energy per year from renewables [a]

1. Fossil fuels	Three 150,000 bpd oil refineries (base case)
2. Hydroelectricity	Canada - James Bay when completed ~19,300 sq. km./EJ - installed capacity 0.8 EJ, delivered 0.5 EJ [b] - All Canada max. installed capacity [c] ~4.3 EJ, ~2.5 delivered US -1988 installed 2.1 EJ, 0.9 EJ delivered [d], 0.5 EJ remain. World installed capacity 1995 [e] ~22 EJ, est max. ~45 EJ
2. Biomass fuel [f]	Short rotation trees, 19,000 to 46,000 sq. Km. - world agricultural cropland ~15,000,000 sq. Km.
3. Methanol [f]	50,000 to 120,000 sq. Km. of short rotation trees. - diff. from #2 to #3 is conversion energy wood to methanol
4. Ethanol [f]	32,000 sq. Km. of land suitable for sugar cane.
5. Wind [f]	~1,000 sq. Km of towers, roads, etc. from ~20,000 sq. km [12] 268,000 turbines @ 0.5 MW, 300-400 m apart. Supplement energy up to 20% of grid [12], 1998 world output ~ 0.075 EJ [26]
6. Solar-H_2 [f]	a) 32° Lat. Tucson, AZ: PV cells on 2,970 sq. Km. b) 48° Lat.- Seattle/Timmins/Chicoutimi 9,360 sq. km. - 217,000,000 litres water/day = city of 500,000 people. - safe disposal of oxygen

(a) World consumed 386 EJ of energy in 1995, 329 EJ of fossil fuels.
(b) Estimated 50% to 60% capacity factor.
(c) Ref. 24: Electric Power in Canada 1997, CEA/NRCan
(d) At 40% capacity factor.
(e) Ref. 24: Energy Statistics Yearbook, 1995. United Nations 1998.
(f) Ref. 25: Lightfoot and Green

Slide 12

Renewable energy for 10 EJ, one year out of 110

	10 EJ = 1 yr out of 110	Equiv. fossil fuels, years	Time to achieve from 2001	Comments
Hydro	1	3	20+? years	Develop 75% of remaining capacity
Biomass (solid)	1	1	? years	2% of existing crop land (300,000 sq km), or develop new crop land
Methanol (liquid)	1	1	? years	5% of existing crop land (750,000 sq km), or develop new crop land
Wind	1	3	18 years	200,000 sq km of land. Land added at rate of 52,000 sq km/yr
Solar	1	3	36 years	20,000 sq km of land. Land added at rate of 5,200 sq km/yr
Total	5	11	-	Out of 110 years

Slide 13

World electricity supply from nuclear fission is growing.[15]

Type of energy, EJ	1970	1995	2010
Oil	-	13.8	
Natural Gas	-	23.4	
Coal	-	53.5	
Nuclear	0.9	24.6	
Renewables	-	31.8	
Total	-	147.1	
Electricity Output[14]	15.5	42.5	~60
Average efficiency		28.9%	
Total World Energy		385.7	~500

% by fuel type:[13]

63.8% Fossil fuel
18.6% Hydro
17.3% Nuclear
0.3% Other

In 1999 there were:[27]

435 nuclear plants producing electricity in 30 countries
38 new nuclear plants under construction in 13 countries.

1 EJ of electricity requires 53 nuclear plants of 1000 MW at 63.5% capacity factor consuming ~3 EJ of nuclear fuel.

Nuclear fission energy is carbon-free energy. Uranium reserves up to few centuries - depends on growth rate

How fast and how far will nuclear fission grow?

Nuclear Fusion:

A long term project, several options, expensive research, unlimited heavy water fuel, no long term radioactivity problems, may be decades away, must be pursued.

Slide 14

Hydrogen is not a source of energy.

Most hydrogen made today - steam reforming of natural gas, the process discharges CO_2 and requires at least 1.5 units of energy to produce 1 unit of energy as hydrogen.

1 EJ of hydrogen = ~37 nuclear plants, 1000 MW, 100% C.F., 90% Util., consuming ~4 EJ of uranium. Water for hydrogen = enough for a city of 500,000. Safe oxygen disposal.

The "hydrogen economy" needs large sources of carbon-free energy to manufacture the hydrogen.

Hydrogen is very light. It has a low energy to volume ratio as a gas or as liquid. It is liquid at or below -253°C.

A comparison of some Higher Heating Values (HHV):

	Joules/kg x 10^6	Joules/m^3 x 10^6
Gasoline	48	35,649
Liquid hydrogen	142	9,936
Methanol	24	19,001
Natural gas	56	37
Hydrogen gas	142	12

Hydrogen: energy intensive, not easy, very long term, if ever.

Liquid hydrocarbon fuels: high energy to volume ratio - preferred fuel for transportation. Save oil for transportation fuel and chemical feedstocks.

Slide 15

Conclusions:

1. Stabilization of CO_2 concentration in the atmosphere is a difficult task. There are no simple solutions!

2. Increases in energy efficiency can displace about one half to two thirds of the carbon-free energy otherwise needed to stabilize the level of CO_2 in the atmosphere at 550 ppmv.

3. Renewable energies require too much land - important, relatively small role - 5% to 10% of world energy supply.

4. People will have to adjust to higher levels of CO_2 in the atmosphere. Energy is too vital to "just turn off the tap".

5. Large sources of carbon-free energy are needed if the level of CO_2 in the atmosphere is to be stabilized at 550 ppmv.

6. Conservation is desirable, but is not a solution. It is a small and variable component of the climate stabilization picture.

7. Not a "doomsday" scenario, but a "wake-up call". Solutions must respect the well-being of people and the environment.

Slide 16

Corollary:

Efforts to find new energy sources and technologies require far more than simply "getting energy prices right".

Artificially raising fossil fuel prices before alternatives are available may create severe economic hardships.

Regardless of fossil fuel prices, no substitutes or technologies are available to replace fossil fuels on the scale needed.

Slide 17

How can the problem of stabilizing the level of CO_2 in the atmosphere at 550 ppmv be resolved?

The developed world can:

1. Vigorously pursue energy efficiency - implementation at home and in less developed countries; search for new technologies.

2. Vigorously pursue new, large sources of carbon-free energy capable of supplying 1,188 EJ to 1,890 EJ annually in 2100.

3. Ensure an adequate and affordable supply of fossil fuels until sufficient carbon-free energy is available.

4. Provide sufficient and stable long term funding - possibly a modest dedicated tax on consumption of fossil fuels.

5. Practice conservation - not a solution, but a small contribution each person can make, a step in the right direction.