Future world energy constraints and the direction for solutions

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Abstract

This paper was originally written in response to the concern that rising levels of CO_2 in the atmosphere caused by burning of fossil fuels will ultimately contribute to global warming. Now we are beginning to see evidence of coming problems in the supply of fuels for transportation. This paper describes the benefits of adequate energy supply and the problems of future energy supply. Partial solutions are suggested for immediate application as well as longer term solutions to address both of these concerns.

To evaluate the situation and solutions we must understand: (1) how much primary energy is currently used world-wide and might be needed in 2100, (2) how important energy is to the welfare of people, (3) the forms of energy sources and end uses and (4) where new sources may come from.

The major portion of world primary energy demand is provided by fossil fuels. This portion dropped from 93% in 1970 to 85% in 1995, mainly because of the increased use of nuclear energy. However, since the mid-1990s fossil fuels have maintained their 85% share of world energy supply.

The importance of the relationship between per capita energy consumption and per capita income for the world is discussed. The limits of conservation, energy efficiency and renewable energies are examined. The contribution of renewable energies is compared to 41 different views of world energy demand in 2100. Without new technology for large scale storage of intermittent electricity from wind and solar the contribution of renewable energies is not likely to grow significantly beyond the current level of 7-8%.

The paper offers conclusions and partial solutions that we can work on immediately. Examination of the forms of energy supplied by the sun, which is powered by nuclear fusion, and the way in which nuclear fission currently supplies energy to the world sets the research framework for longer term solutions. This framework points towards two possible longer term complementary research projects which take advantage of the concentrated energy and portability of nuclear fission: (1) to find ways of extending nuclear fission to smaller transportation and heating applications and (2) to develop nuclear fusion for manufacturing fissionable materials.

This paper is in the form of a presentation using overhead projector slides with a written commentary for each slide.

Slide 1. Future world energy and the direction for solutions

This presentation is updated and expanded from McGill University Centre for Climate and Global Change Research (C^2GCR) Report 2001-1 “Climate change is and energy problem", March 2001, which was co-authored by Christopher Green, Dept. of Economics, McGill University and the Centre for Climate and Global Change Research. Selected references are included at the end.

Slide 2. Global carbon cycle

Carbon is recycled naturally into and out of the atmosphere, vegetation and the oceans in the form of carbon dioxide (CO_2).

Historically, on average, the vegetation/soils cycle has been in balance. In the vegetation cycle, plants take in CO_2 from the atmosphere, combine it with water through photosynthesis and release oxygen to the atmosphere. When vegetation dies, decays, is eaten, or burned the CO_2 is released back into the atmosphere. From the upper right hand graph, all CO_2 taken up by vegetation is between May and September.

The average absorption rate of CO_2 into the ocean has naturally been consistently slightly higher than the release rate over hundreds of millions of years and the oceans have accumulated immense quantities of dissolved CO_2, especially in the deep oceans.

Humans have added two new sources of CO_2 to the atmosphere - burning of fossil fuels which discharge 5.5 GtC/yr of carbon to the atmosphere and land use changes such as deforestation contribute a net of about 1.1 GtC/yr[1] for a total of about 6.6 GtC/yr of carbon.

This new source of carbon throws the cycles out of balance and the amount of carbon being absorbed has increased. It appears that almost half remains in the atmosphere and the remainder is split about equally between the oceans and vegetation/ soils. Each year the concentration of CO_2 in the atmosphere increases an average of 1.5 ppmv.

A slight change in conditions, such as a rise of atmospheric temperature or saturation of the vegetation with CO_2, and vegetation, such as forests, and become a source of CO_2 to the atmosphere. The situation is similar for the oceans. Thus, vegetation/soils and oceans are unreliable places to store carbon.

This version of the Carbon Cycle is from the Hadley Centre in the United Kingdom[2].

Slide 3. Historic levels of CO_2 in 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 [3] 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[4]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[5].

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 2003 was a high of 378.35 ppmv at the end of the winter, and a low of 372.99 ppmv at the end of the summer in the northern hemisphere[1]. 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 for fuel 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 IS92a. Point K, calculated by James A. Edmonds[6], 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 which has not signed onto Kyoto.

The WRE 550[7] line represents what might be a reasonable path to a target concentration of CO_2 in the atmosphere of 550 ppmv.

Without the greenhouse effect of CO_2, which is the major greenhouse gas, and other minor gases, the atmospheric temperature would be $-18^{O}C$[8] 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.

It is not clear why CO_2 concentration dropped and caused the ice ages, or why it rose again causing atmospheric temperature to rise and melt the ice.

Slide 4. Sources of greenhouse gases

There are several natural factors which affect whether or not atmosphere warms or cools. 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.

[1] Most of earth's land is in the northern hemisphere.

Methane has 30 times the warming effect of CO_2, but breaks down to CO_2 and water in ten years. 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.

There are also man-made factors which warm or cool the atmosphere. By far, the largest of the man-made sources of atmospheric carbon is CO_2 from the production and use of fossil fuels. Methane is a smaller factor and is released by several human activities, such as farming of ruminant animals where part of their digestion is a fermentation process that releases methane. Biomass burned at too low 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 warming effect.

With an increase of 30% 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.

It does not matter where the CO_2 comes from, combustion of fossil fuels or natural sources, when the concentration of CO_2 goes up or down the temperature follows[9]. The question is not whether or not the temperature will increase but, "How much by 2100?"

This temperature record shows a measurable increase of about $0.6^{O}C$ in the earth's average atmospheric temperature since the late 19^{th} century when the atmospheric concentration of CO_2 was about 295 ppmv[10].

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. . For example, the dip in atmospheric temperature after 1991 was caused by dust from the eruption of Mount Pinatubo on June 15, 1991.

Carbon dioxide is not all bad. It is a nutrient for plants, which are at the bottom of the food chain for every living organism. Generally, plants grow faster in higher concentrations of CO_2 and use less water. This is one factor in the record of increased yields of food crops. Further, trees are beginning to encroach on the Negev Desert because they need less water and can expand their range to drier areas.

Slide 5. Reducing CO_2 emissions and providing adequate future energy supply

Most people believe that reducing CO_2 to an acceptable level can be accomplished by sequestration or capture of CO_2, conservation, energy efficiency increases and the extensive use of renewable energies or a combination of all of these.

Are these solutions? Are new solutions needed?

This paper answers these questions

Slide 6. World energy consumption (EJ/yr)

It is necessary to talk about quantities of energy to provide a rational look at the problems and possible solutions. The unit of energy used throughout this presentation 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.

World energy consumption by fuel type was 204.2 EJ in 1970, 385.7 EJ in 1995 and an estimated 457.3 EJ in 2005.

The percentage of fossil fuels i.e., coal, oil and natural gas, 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, and has remained at 85% since then.

Currently, only fossil fuels can supply the world's energy requirements

Slide 7. Energy - uses, sources and forms

It is important to know how we use energy and where it comes from.

Electricity generation consumes about 2/5 of all world energy consumption and uses all forms of primary energy. Fossil fuels account for about 60% of the energy used to generate electricity and coal by itself accounts for about 35%. Hydro is the largest and most important of the renewable energies.

Transportation energy is 97% oil simply because there are no substitutes for oil on the scale needed. Transportation represents approximately 1/5 of world energy consumption.

Residential, industrial and commercial account for about 2/5 of world energy demand and consume electricity from electricity generation in addition to oil and natural gas.

Slide 8. History & projections of world energy consumption[2]

Historic world primary energy consumption is shown from 1970 to 2000. A projection made by the Energy Information Administration (EIA) to 2025, and the IPCC IS92a "business as usual" scenario from 1990 to 2100 are also shown for purposes of comparison.

World energy consumption was about 347 EJ in 1990, of which 47 EJ was carbon-free energy. In IPPC scenario IS92a, 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.

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[2] 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[2]. 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/yr.

The IPCC IS92a and carbon-free energy[3] curves 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 vegetation and soils. 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.

Four times current world energy demand is a tremendous amount of energy. It will become increasingly difficult for fossil fuels to supply this energy as the supply dwindles. Oil is already becoming supply restricted, and provides 97% of transportation energy.

Why is energy consumption expected to grow by four times? There is a positive correlation between energy consumption and increasing population and income per capita. The population growth gradually decreases and flattens out at 11.3 billion in 2100[7]. However, income per person is a stronger force to increase energy consumption as shown on the next slide, and has an historical rate of increase of 1.6% average from 1890 to 1990, and it is expected to maintain or exceed this rate for the next hundred years.

Both the IPCC IS92a and carbon-free curves have built-in average annual reductions in energy per unit of output of 1% per year, i.e., energy intensity decline, for the 110 year period 1990-2100. From work that will soon be published, this rate of 1% is a maximum and will not be easy to achieve. Thus, the 1,453 EJ/yr shown here is a minimum and the actual energy required for this scenario could be higher and above the top of the chart.

Slide 9. Problem: How do we increase energy use and reduce carbon emissions when energy is 85% fossil fuels?

The "Power" line shows a strong positive correlation between Per capita mean GDP (Gross Domestic Product) (GDP/N), or income per capita, and Per capita mean power consumption (E/N).

Energy = wealth and freedom. The people living in the countries shown in the upper right corner use one hundred times more energy and have one hundred times the income of those who live in the countries shown in the lower left corner.

Those people living in countries in the upper right of this chart have much more control over their lives, more freedom of choice, better medical care, more and better food, etc. Most people in the world are trying to move up towards higher income and, therefore, more energy consumption per person. Those living in developed countries are helping people in less developed countries to move higher up the energy consumption line.

This, and the fact that most of the world's population live in countries shown in the lower left corner of the chart explains why the Gross Domestic Product per capita (GDP/N) is expected to grow throughout this century by +1.6% annually.

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[3] The curve of carbon-free energy required to stabilize the level of CO_2 in the atmosphere at 550 ppmv was prepared by Wigley, Richels and Edmonds (WRE 550), Nature, October 29, 1998[7].

It appears that even if the population growth rate levels off sooner than expected, there will still be 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.

The "Carbon" line is from IPCC Working Group III in Climate Change 2001: Mitigation in 2001, Figure 1.5[11]. It shows a strong positive correlation between carbon emissions and per capita GDP, or income, as expected because world energy supply is 85% carbon emitting fuels, i.e., coal, oil and natural gas.

The key point here is that plans for reducing world carbon emissions have to be very well thought out to avoid adversely affecting the real income of the world's people. For example, reducing carbon emissions by 25% will reduce real income by 25%. To avoid such a reduction of this magnitude likely requires a carbon-free source of energy to replace the fossil fuels.

Slide 10. What does GDP per person mean to us?

The amount of GDP per capita or income per capita is represented by all of the goods and services we consume or have at our disposal. This is wealth that energy has given us. These are the things that give us control over our lives – they help us to live full and useful lives.

The items shown are only examples from a very long and comprehensive list. Each item is there because of our extensive use of energy. From the previous slide it is evident that reducing energy consumption per person would reduce income per person and, therefore, would eliminate or sharply reduce the availability of items on this list.

Transportation is an essential component of each item on the list.

Think carefully about which items on this list that you would cut if you were asked to reduce energy consumption by one quarter. This becomes a difficult task because we do not know how much energy each item represents. Even if we knew this, it would be very difficult to choose where to cut. This is especially true if a group had to decide to make the cuts, because the items on our list are of some importance to all of us at some time and of significant importance to some of us all of the time.

There is no doubt that energy is vital to our everyday lives.

Slide 11. Carbon sequestration – capture and permanent storage of CO_2

To counter the CO_2 from burning fossil fuels it has been suggested that the CO_2 be captured and permanently stored, i.e., sequestered. This means to capture CO_2 from smokestacks and other sources of CO_2.

The capture of CO_2 is energy intensive because in smokestacks it is usually diluted to a range of 3%-15%[12] with other gases, such as nitrogen, from the combustion air. The energy penalty is 14%-28%[12]. Currently, some CO_2 is being captured from flue gases and being sold commercially. Some is used in products such as dry ice which eventually return the CO_2 to the atmosphere, and some is used for pressurizing oil wells to increase production and is captured, possibly, permanently.

CO_2 in gaseous form can be disposed of by pumping into oil wells or gas wells or into saline aquifers deep underground. This is limited by suitable proven and stable locations. Other proposals would liquefy the CO_2 and disperse it in the deep ocean below about 3000 metres[12], or combine CO_2 gas with stable minerals, such as magnesium silicate in the mineral serpentine.

Large scale sequestration of CO_2 would consume large quantities of energy, thereby requiring more sequestration. The world's reserves of fossil fuels would diminish more rapidly.

The rate of carbon sequestration by natural methods is not constant, may vary widely and even reverse to become a source of CO_2.

Historically, the rate of CO_2 dissolving in the ocean has exceeded the rate of releases and much CO_2 has accumulated, especially in the deep oceans. It continues to do so. However, the recycle rate could change if the ocean surface became saturated and the oceans could become a source of CO_2. On the positive side, the population of phytoplankton may increase from CO_2 fertilization and more carbon may be carried to the bottom of the ocean as they die.

As the level of CO_2 increases in the atmosphere, plants grow faster and require less water and soils accumulate more carbon. As rates of growth and decay are continually changing, vegetation and soils may not always be in balance. Further, a saturation level may be reached where the recycle rate is balanced and vegetation and soils are no longer a sink for CO_2. Thus, natural sequestration methods do not store CO_2 in reliable carbon storage sinks.

Slide 12. Energy conservation – a personal choice.

Conservation helps a bit but is not a solution. 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.

Conservation is a matter of opinion. 4 dogs ≈ 1 SUV - the energy to keep one dog is about one-quarter of the difference in energy consumption between an SUV and an ordinary car. Look at the long line of pet foods in the supermarkets – it takes lots of energy to grow, process, package, and transport pet food as well as energy for pet health. Why should people be allowed to keep dogs? People keep dogs because the dogs make them feel better about themselves.

This gives some idea of the controversial nature of conservation - one person's necessity may be considered unnecessary by someone else.

The point is that people use energy to make themselves feel better, and energy to acquire their lifestyle, and there is definitely no agreement on life styles.

Although the contribution of conservation is very small, we must all conserve in our own way.

Slide 13. Possible future energy efficiency increases.

Energy per unit of output is the definition of energy intensity. Energy intensity decline is used by economists to describe declining nature of the values in the curves of this slide. An increase in energy efficiency results in a decrease in the amount of energy used per unit of output, i.e., there is a decrease in energy intensity. There is also a decrease in the amount of energy used per unit of output when less energy intensive industries, such as service industries, become a larger part of the economy relative to energy intensive industries such a iron and steel. Historically, energy intensity decline is about 80% increases in energy efficiency and 20% sectoral changes in the economy.

Increases in energy efficiency reduce energy per unit of output and depend on technology. They become more difficult to find and implement as the physical limits to energy efficiency are approached, i.e., thermodynamics, friction, strength to weight ratio, etc. This is shown by the asymptotic shape of the curves.

If an average 1% annual reduction in energy per unit of output could be maintained for 110 years, energy per unit of output would drop to 1/3 in 2100 of what it was in 1990. Realistically, for about half of the world's energy consumption, mainly electricity generation and transportation, energy per unit of output can be reduced to about ½ of the 1990 level because of physical limitations. For the average to drop to 1/3, energy per unit of output for the remaining half of energy consumption would have to drop to 1/10 of that in 1990. This is likely unrealistically low because of physical limits. Thus, it is unlikely that an average annual reduction of 1% can be achieved, and world energy consumption would be higher than the 1,453 EJ/yr of IS92a, which is based on 1%.

Slide 14. Maximum world renewable electricity & biomass

This table was constructed using area required per 1 EJ of energy from various sources to give a range. The land available for each is as estimated by IPCC Working Group III (WG III) in Climate Change 2001: Mitigation[13]. The EJ available from each energy source is calculated by dividing the land available by the area per EJ.

The renewable energy is divided into three categories according to the form of energy that is actually available for use, i.e., intermittent electricity, electricity that can be delivered on demand, and biomass energy.

Solar and wind energies deliver intermittent electricity to the energy system and require 100% back-up for when these sources are interrupted. Fossil fuel generating stations must keep their system running in "spinning reserve mode", i.e., burning fuel to keep the steam pressure up and the generators turning, but producing little or no electricity, so they can deliver electricity immediately the wind or solar are interrupted. The limit is 20% of installed capacity or about 10% of annual fossil fuel electricity output.[11][14] Hence the sharp reduction of solar and wind electricity that can be used. Note that because 100% backup is required for wind and solar, the value of wind and solar electricity is the value of the fossil fuel displaced, i.e., 1-2 cents/kWh when coal is the fuel.

In this particular example, the amount of fossil fuel electricity generated is calculated using the total electricity of 968 EJ/yr in IPCC Working Group III scenario A1B-Mini-CAM, which has the largest amount of electricity in final energy of any of the 40 scenarios. Similarly, B2C-MARIA has total electricity of 153 EJ/yr, which is the lowest of the 40 scenarios. The range of net renewable energy calculated on this basis is 98-251.5 EJ/yr. For comparison with the scenarios on the next slide, these numbers are converted to the fossil fuel equivalent[4], i.e., the Energy Information Administration (EIA) definition of primary energy, of 164-429 EJ/yr.

Hydro, which delivers electricity on demand, is limited by suitable sites, about half of which have been developed.

Slide 15, Maximum contribution of renewable energy

This slide shows 41 different ways of looking at world energy demand in 2100 – IS92a and 40 scenarios prepared by IPCC Working Group III (WG III) in the Special Report on Emissions Scenarios[15]. All primary energy values shown on this slide are by the EIA definition of primary energy, i.e., the fossil fuel equivalent.

The effect of large scale sequestration of CO_2 would be to move all of these points upwards because sequestration requires energy, and lots of it.

Conservation has a small effect and would move the points slightly downward.

All of the points have a maximum of 1% annual increases in energy efficiency, or less. Therefore, if 1% average annual increase in energy efficiency is not achieved, most of the points will move higher.[5]

World renewable energy consumption in 2100 of 34 EJ is shown as the lowest line and is 8% of 2001 world energy consumption.

The range of maximum renewable energy is 11% to 30% of IS92a world energy demand in 2100.

It is not likely that large scale storage of electricity, intermittent or otherwise, will ever be achieved. However, if it were achieved and 50% of the original energy could be recovered

[4] The Energy Information Administration (EIA) records electricity from renewable energies at 3.05 units of primary energy for each unit of electricity produced. Nuclear primary energy is recorded as the actual amount of uranium used for each unit of electricity produced. WG III records one unit of primary energy for each unit of renewable and nuclear electricity produced. See page 221 of the Special Report on Emissions Scenarios.

[5] The primary energy in those WG III scenarios with annual reductions in energy per unit of output (energy efficiency increases) greater than 1% annually have been adjusted upwards accordingly.

as electricity when needed, then the contribution of renewable energies would be about as shown. This estimate of 50% recovery compares with pumped storage of about 70% recovery and solar hydrogen used in fuel cells of 40%-45%. Neither of the latter is viable on a sufficiently large scale to make a significant difference.

No matter how one looks at world energy demand in 2100, renewable energies together with conservation and energy efficiency increases provide a small contribution.

Slide 16. The Hydrogen Economy - H_2 is a manufactured energy

Today, more than 90% of hydrogen is manufactured from fossil fuels and more than one-half is manufactured from natural gas, which requires 1.5 joules of natural gas energy for each joule of hydrogen energy produced. For the same energy release, hydrogen made from natural gas releases 150% more CO_2 to the atmosphere than burning the natural gas directly. Hydrogen made from fossil fuels is only environmentally friendly if the CO_2 is sequestered. This would only make sense if there were a reliable and energy efficient process for sequestering the CO_2.

More than 90% of the hydrogen produced today is used for chemical processing where hydrogen is essential to the process.

Using electricity to manufacture hydrogen is using a manufactured energy to manufacture a second energy.

The electrochemical reaction is: $2H_2O + \text{DC electricity} \rightarrow 2H_2 + O_2$

Hydrogen by electrolysis of water from any source of electricity is costly and impractical on a large scale, although there are small niche applications[16].

A chlorine/caustic soda plant and a hydrogen plant are very similar. We know the selling price of chlorine and caustic soda over a five year period. From this, the cost of the hydrogen produced can be reliably calculated to be the equivalent of oil at $270 to $540 per barrel. Electrochemical companies purchase the lowest priced electricity in their area because the generators supplying the electricity run at, or near, maximum efficiency continuously.

It is often suggested that solar electricity be used to manufacture hydrogen. This requires enormous facilities. Suppose, for example, solar electricity from photovoltaic cells were used to generate 1EJ/yr of liquid hydrogen in Luxor, Egypt - an area with the highest solar insolation in the world. The area of land required would have to be $2250km_2$, (almost three quarters the size of Rhode Island) to provide sufficient electricity to electrolyze the water into hydrogen and oxygen, to cover transmission and conversion losses, liquefaction of hydrogen for shipping, 5% of hydrogen for power supply when the sun is not shining, etc.

One EJ/yr of hydrogen would power the world's transportation system for about one week. It requires 239,000,000 litres of water per day, which is enough water for a city of 500,000 people. The water has to be of distilled water quality (<1ppm solids, 1-2 megohm/cm) to prevent degradation of the electrolyte in the electrolyszer cells. The local water supply would be the Nile River and 40 tonnes per day of suspended and dissolved solids would have to be removed. The building housing the electrolyzers would occupy an area of about 500 football fields.

For each kilogram of hydrogen produced, 8 kilograms of oxygen is produced. Oxygen is a hazardous material and has to be disposed safely. Dilution to a safe level of 23 % before discharge to the atmosphere would require as much air per hour at peak production rates as there is in a line of Goodyear blimps nose to tail 9,000 km long every hour.

It becomes clear that the large facilities required to produce a relatively small amount of hydrogen fuel make the process impractical.

Slide 17. Nuclear energy - carbon-free and growing

Nuclear fission energy is growing. It now makes the same contribution (19%) to world electricity production as hydro and other renewable energies (20.6%) and natural gas (19%), more than twice as much as oil (7.5%), and more than half that of coal (34%).

Nuclear grew rapidly from 1970 to 1995 and is the principal reason why the share of fossil fuels fell from 93% in 1970 to 85% in 1995. The rate of growth has fallen, but is still faster than the growth rates of electricity and world energy consumption.

The growth of nuclear energy is projected by the EIA to stall in 2020 at 31 EJ, about the level in 2001. The capacity of nuclear generating plants being shut down is expected to about equal that of new ones being built. However, electricity consumption grew from 15.5 EJ in 1970[17] to 50.2 EJ in 2001[18] and is projected to grow by another 28.8 EJ/yr to ≈ 79 EJ in 2020. It is difficult to believe that nuclear will not play as dominant a role as in the period 1970-2001.

A major limitation of nuclear energy is the shortage of high grade uranium – it may only last 1 to 2 centuries at current growth rates.

Slide 18. Where are we now? - not a *Doomsday* scenario but a *Wake Up Call*

Stabilizing the level of CO_2 in the atmosphere is a difficult task. There are no easy or simple solutions.

Conservation is far too small and controversial to be a solution, but we must all conserve energy whenever we can.

Efficiency is something we can do now and has an immediate benefit, but is only a partial solution.

Renewable energies can only make a small contribution because land available is limited and only a small part of the intermittent electricity that might be available can be used. Nevertheless, we need all that it makes sense to develop.

People must adjust to higher levels of CO_2 in the atmosphere simply because energy is too vital to just turn off the tap – solutions are a long way off.

Large sources of carbon-free energy are required if CO_2 is to be stabilized at 550 ppmv and adequate supplies of future energy are to be provided.

The analysis to here identifies and describes the problem.

Next, we examine potential solutions - where new sources of energy might come from. But first, an important message on the next slide.

Slide 19. Taxes & subsidies – won't higher fossil fuel prices encourage alternative technologies?

Discovery and development of new energy sources & technologies requires much more than "*getting energy prices right*".

No alternatives exist to replace fossil fuels on the scale needed.

Therefore, artificially raising fossil fuel prices before alternatives are available is likely to create unnecessary economic hardships.

Slide 20. Three prime sources of energy on earth

There are only three sources of world energy supply available to us on earth – gravity, nuclear fusion (combining atoms) and nuclear fission (splitting atoms).

The gravity of the moon causes tides from which we can extract a small amount of intermittent electricity. Gravity also works with the sun through the hydrological cycle to provide hydro electricity.

Nuclear fusion powers the sun which in turn provides renewable energy in the form of sunlight, wind, wave, hydro and biomass.

Over hundreds of millions of years, biomass has been stored and converted to coal, oil and natural gas – non-renewable energy. Today 97% of transportation fuel is derived from oil, about one-third of our electricity comes from burning of coal. More than 90% of the world's hydrogen production is from fossil fuels and more than half is from natural gas. Today, hydrogen is not a fuel - more than 90% is used for chemical processing where hydrogen is required in the process.

It has been proposed to provide electricity to the world by building huge solar arrays in space to overcome the limitations of land area and intermittency of the electricity produced. The electricity produced would be transmitted to earth by microwaves to large areas of antennae. Many things in space are possible, but at a price – often very expensive. Significant power delivered by such a system is, at best, uncertain and very long term.

Nuclear fusion may one day provide heat for steam to generate electricity, but this appears to be a long way off.

Nuclear fission provides geothermal energy. It also provides steam to generate electricity. As we saw this is a viable and growing industry throughout most of the world.

Nuclear fission also is used as fuel in specialized transportation applications such as the propulsion systems of large ships and submarines as well as in space probes such as Cassini used to explore Saturn and the planned Jupiter Icy Moons Orbiter (JIMO).

Nuclear fission technology is well enough developed that its use can be expanded immediately in its current uses and into residential, industrial and commercial applications and nuclear fission propulsion systems.

However, there is a shortage of nuclear fuel as we saw in a previous slide. Therefore, a means of manufacturing fissionable materials is required. One nuclear fission breeder reactor can provide fuel for, perhaps one reactor using the nuclear fuel. However, one fusion reactor manufacturing fissionable materials might supply enough fuel to ten fission reactors using the fuel,[19][20] and would provide an adequate and long term supply of nuclear fuel.

These two research projects, expanded use of nuclear fission into all energy sectors and nuclear fusion manufacture of fissionable materials, will require much effort to achieve success. If success is forthcoming, then nuclear fission becomes the one and only source of energy capable of replacing fossil fuels and providing the world's energy demands to 2100 and beyond.

Nuclear fission is currently limited to specialty transportation applications because of the weight of shielding required to protect people from neutrons generated by the fission process. Whether or not the use of nuclear fission can be expanded to many more transportation applications depends on whether or not this problem can be solved in some way by materials or processes.

The importance of transportation to the well-being of people and the environment cannot be overemphasized. The current short supply situation of oil is likely to continue and get worse as world production reaches a peak and demand continues to increase. It is important to find a suitable alternative transportation fuel that can be available on the scale needed.

This research program, possibly international and on the scale of the Manhattan of Apollo projects as suggested by Hoffert et al.(1998)[7], would require much fossil fuel energy and human energy. It would be better to carry out such a project while fossil fuel energy, especially oil, is still sufficiently abundant and affordable.

With nuclear fission providing the world's energy, there would be ample time for the development of extracting heat from nuclear fusion if, indeed, it was felt to be necessary.

Slide 21. Conclusions and Implications

This slide reiterates the key points of this presentation. Energy = wealth. Everyone in the world would like more wealth, which means more energy consumption.

Fossil fuels cannot be replaced on the scale needed by combining the contributions of conservation, energy efficiency and renewable energies or by the hydrogen economy.

If the supply of nuclear fuel can be expanded by breeding, then only nuclear fission has the potential to replace fossil fuels on the scale needed, to support four times current world energy use in 2100, provide energy for many centuries, sharply reduce carbon emissions to the atmosphere and, possibly, provide all transportation energy – which is 20% of current world energy demand.

Slide 22. Safety and proliferation of nuclear materials – not issues to stop nuclear fission

Safety is an essential part of any product, process or procedure – hazardous or otherwise. The proliferation of nuclear material is essentially a safety issue. The problems are similar to those of security for the manufacture, shipping and handling of hazardous chemicals and biological materials.

Acknowledgements

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Also the people involved with the McGill University Centre for Climate and Global Change Research (C^2GCR). The Centre 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 faculty of the Centre supervise approximately 60 graduate and postdoctoral students. The web site is: http://www.mcgill.ca/ccgcr/.

Slide 1

Future world energy and the direction for solutions

Presented by

H. Douglas Lightfoot*

***Centre for Climate and Global Change Research (C2CGR)**
McGill University

This presentation is based on C2GCR Report No. 2001-1, March 2001
by
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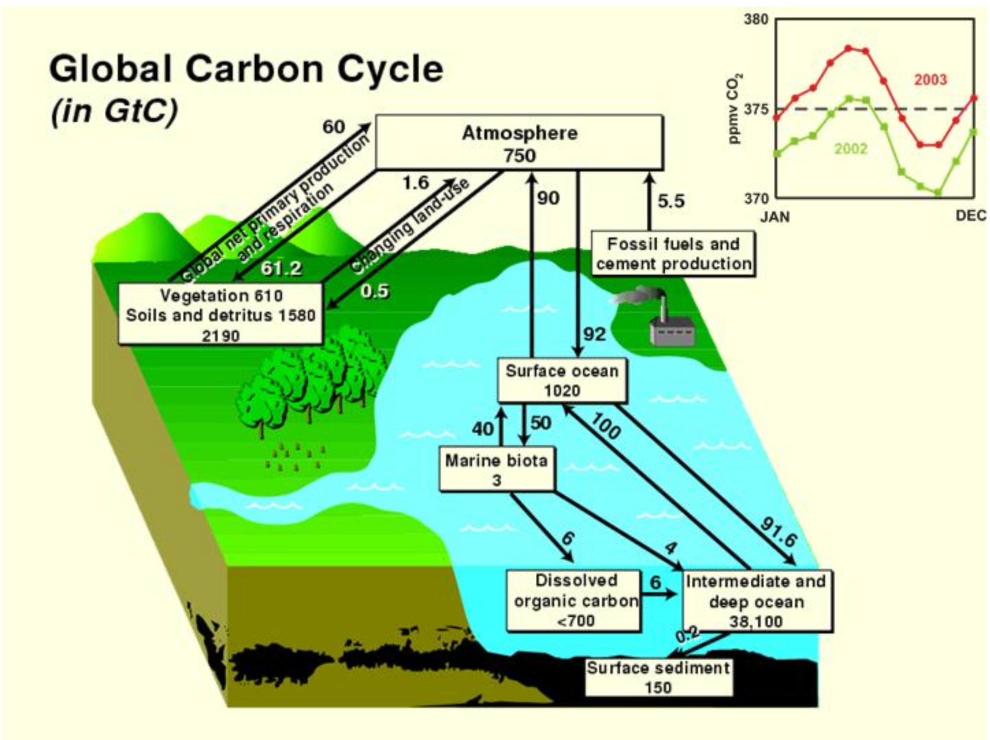
Christopher Green*, Dept. of Economics, McGill University

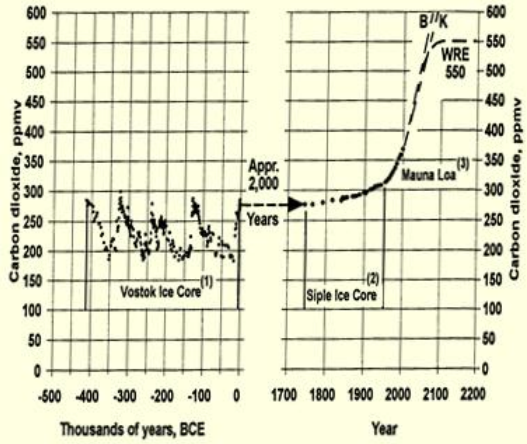
American Nuclear Energy Symposium, Miami, Oct 3-6, 2004

Slide 2



Slide 3

Historic levels of CO_2 in earth's atmosphere



- CO_2 levels directly measured in atmosphere (Mauna Loa)
- B = "Business as usual"; IPCC IS92a
- K = Kyoto target to the year 2100
- WRE 550 at this time a reasonable target

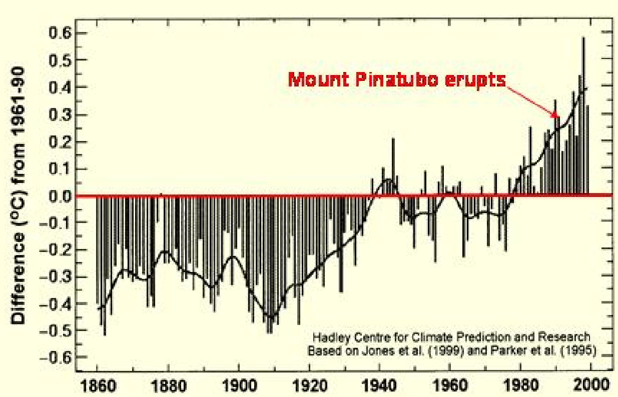
- For the last few millennia, CO_2 concentration has been between 270 and 280 ppmv
- Troughs represent ice ages; peaks are when glaciers melted
- Without greenhouse gases, such as CO_2, earth's temperature would be -18°C

Slide 4

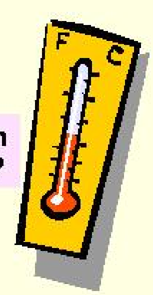
Sources of greenhouse gases

Man-made variables:
Fossil fuel: CO_2 & methane (+)
Methane from animals, growing rice, landfills & burning biomass (+)
Chlorofluorocarbons (e.g., Freon) (+)
Sulfur aerosols from fossil fuels (-)
Nitrogen oxides from fossil fuels (+)

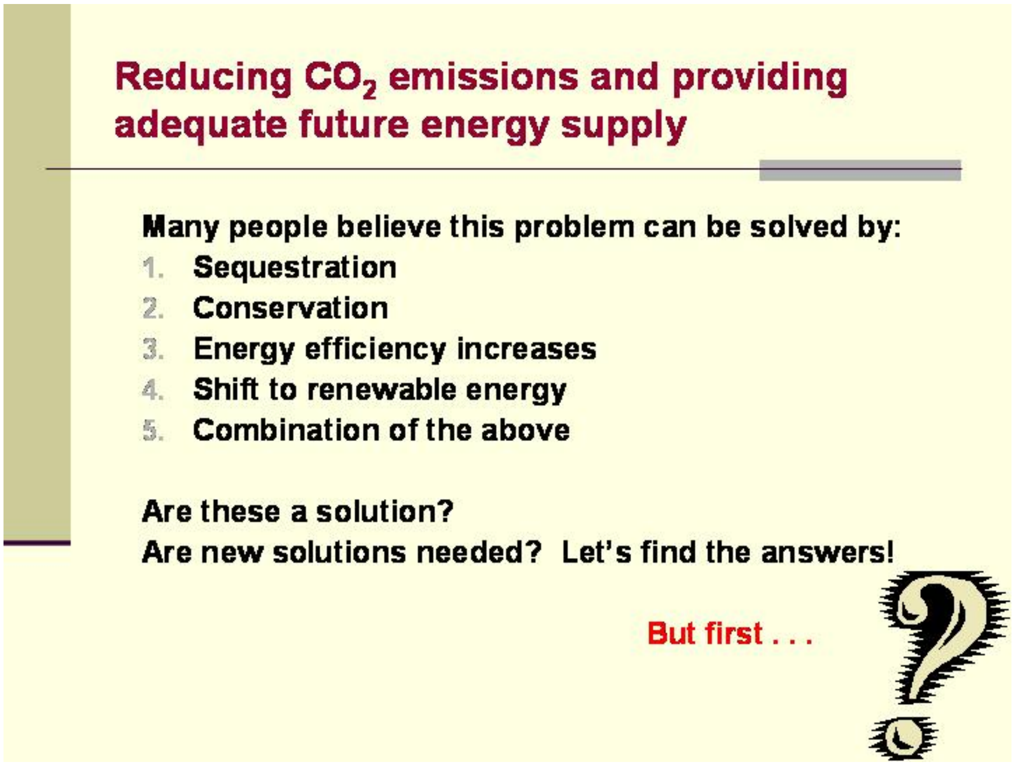
Natural variables:
CO_2 (±)
Water vapour (±)
Solar radiation (±)
Volcanic dust (-) & gases (+)
Methane from wetlands (+)



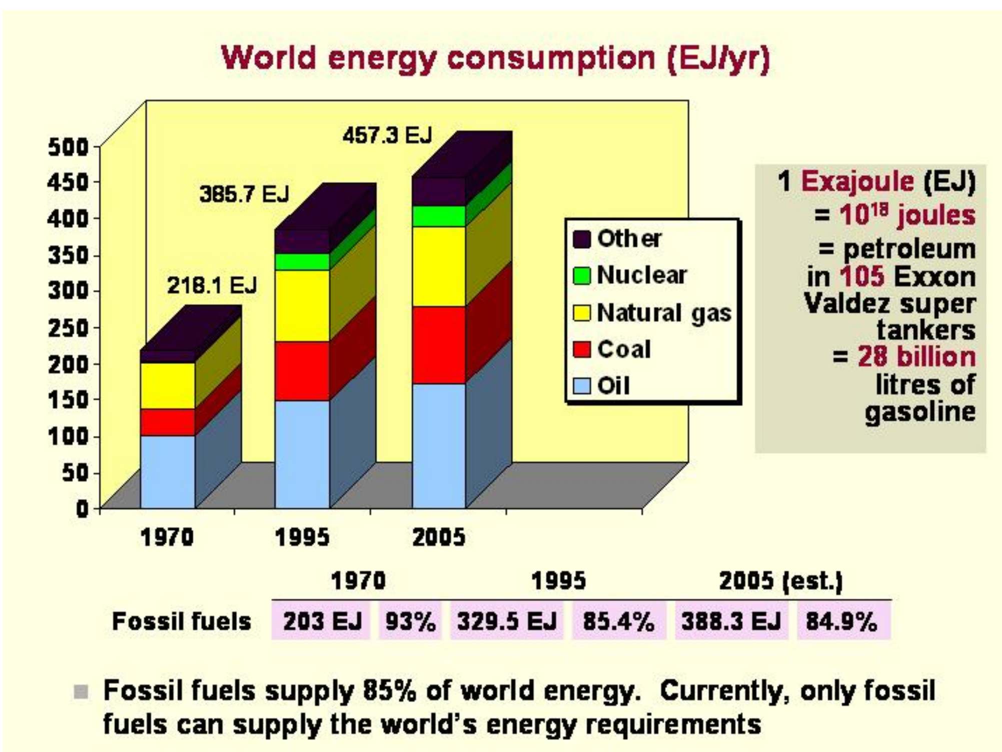
How high by 2100?



Slide 5



Slide 6



Slide 7

Energy – uses, sources, and forms

		Primary energy sources and forms				
Energy uses	Consumed	Oil	Nat. gas	Coal	Hydro*	Nuclear
Electricity generation	137 (37%)	√	√	√	√	√
Transportation	68 (19%)	√	-	-	-	-
Residential	44 (12%)	√	√	-	-	-
Industrial/ manufacturing	80 (22%)	√	√	-	-	-
Commercial/ services	36 (10%)	√	√	-	-	-
Total (1990):	365 EJ					

Notes:

(1) Electricity ≈ 60% fossil fuels, 35% coal

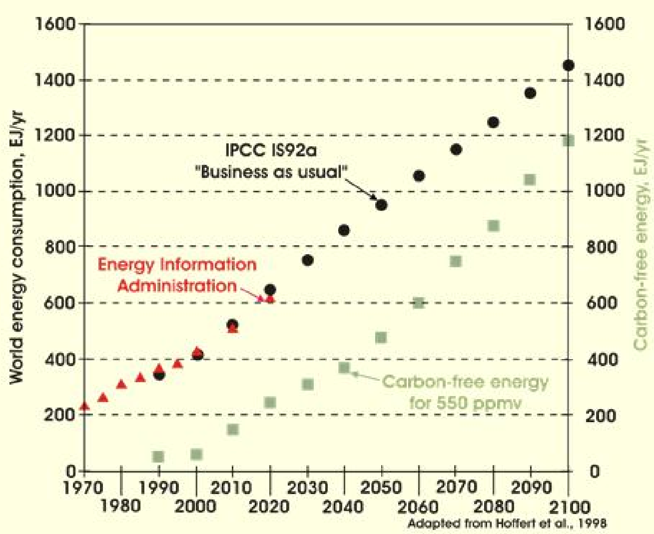
(2) Transportation = 97% oil, ≈ 1/5 of world energy use

(3) Res, Ind, Com. consume oil, gas and electricity

* Includes all renewable energies

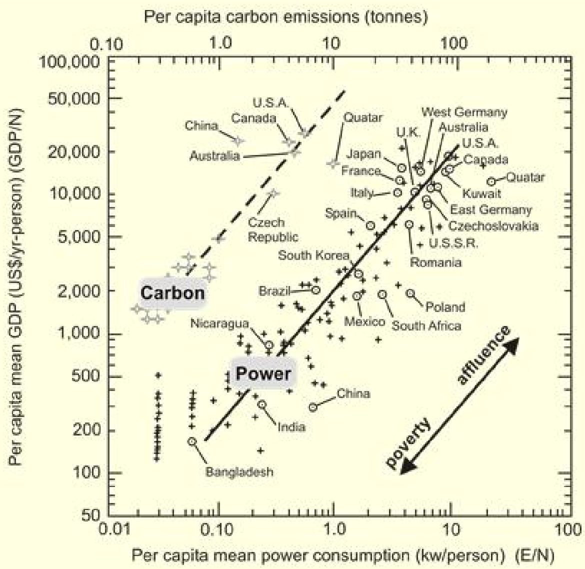
Slide 8

History & projections of world energy consumption



Slide 9

Problem: **How do we increase energy use & reduce CO_2 emissions when energy is 85% fossil fuels?**



Power: +, ⊙ data derived from Hammond (1990, Tables 15.1 and 20.1)

Carbon: data from Climate Change 2001: Mitigation (2001, Figure 1.5)

Slide 10

What does GDP per person mean to us?

GDP means a lot to us . . .

- **Fresh fruits & vegetables all year, drugs & healthcare . . .**
- **Houses, cottages, apartments, hotels, hospitals, lawns & parks . . .**
- **Schools, malls, factories, heating & air conditioning, inside & outside lighting . . .**
- **Pets, toys, fashion, newspapers, TV, movies, cameras, computers . . .**
- **Cars, trucks, trains, ships, airplanes, roads, bridges, canals, airports . . .**

And the list goes on . . .!

Which items would you remove to cut energy consumption by one-quarter?

Slide 11

Carbon sequestration – capture and permanent storage of CO_2

CO_2 capture from smokestacks of electricity generation plants and other processes

- CO_2 is dilute – 14%-28% energy penalty
- Pump CO_2 gas into oil and natural gas fields, saline aquifers, deep ocean, or combine with minerals.
- Large scale industrial CO_2 sequestration:
  – requires huge quantities of energy
  – even more sequestration
  – reduces fossil fuel reserves
- Forests, soils, ocean – conditions change – not reliable carbon sinks

Slide 12

Energy conservation – a personal choice

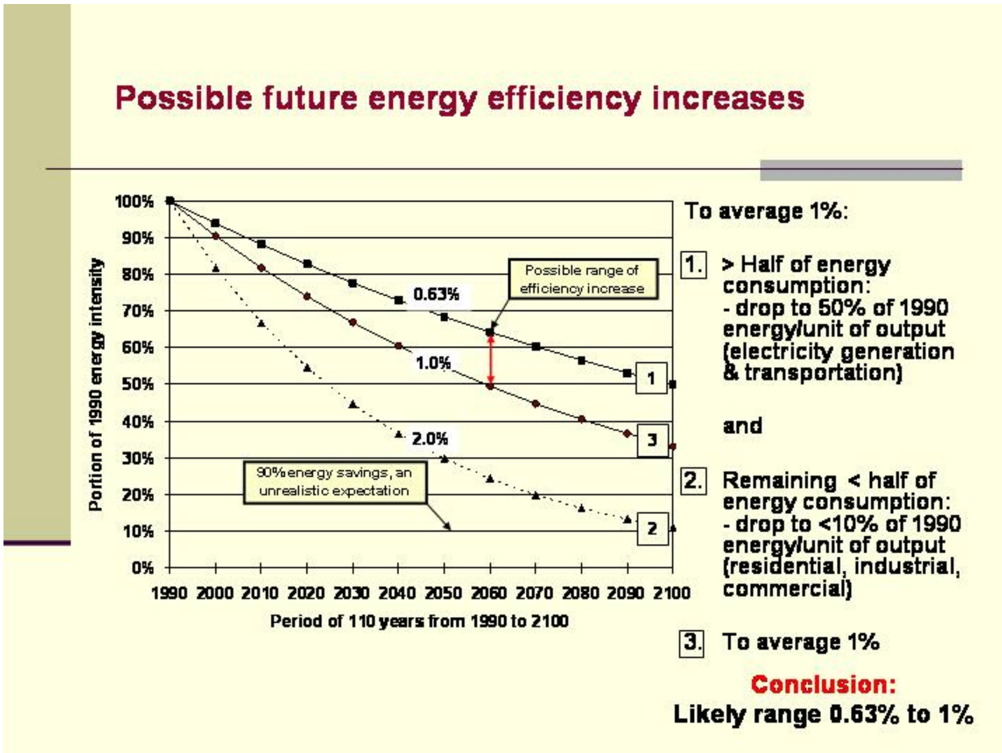
Conservation helps a bit – but is not a solution

Conservation is:

1. Controversial
2. Matter of opinion

   e.g., "*No one needs a pet; let's outlaw dogs*!"
   4 dogs ≈ 1 SUV! "*Ban movies*!"
   "Ban what I think is a frivolous use of energy!"
3. Discretionary – used by people to "feel better"
4. People use energy to acquire their lifestyle
5. Conserve energy!

Slide 13



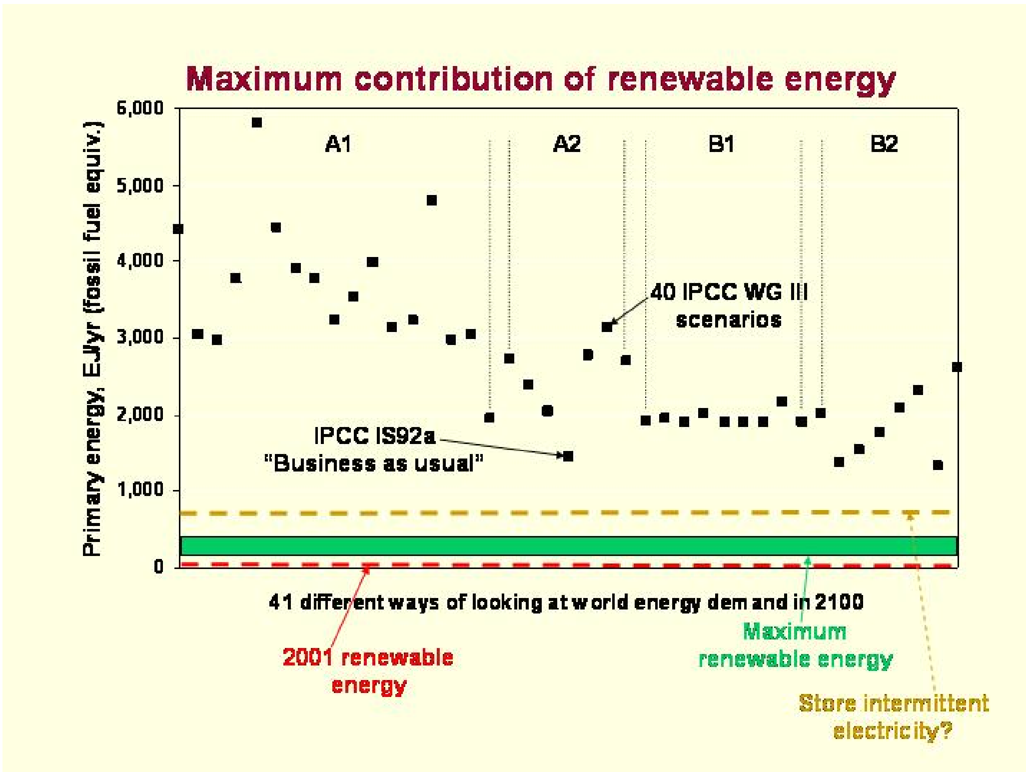
Slide 14

Maximum world renewable electricity & biomass

	Land per EJ of renewable energy km²	IPCC world land for renewables km²	Renewable electricity & biomass liquid fuel	Net usable renewable energy
Intermittent electricity				
Solar	1,905 - 3,333	393,000	118 - 206	Limited to 10% of fossil fuel electricity
Wind	16,670 - 25,079	1,200,000	48 - 72	
Ocean	-	-	1.8 - 3.6	
		Total	167.8 - 281.6	14.5 - 65.7 [1]
On-demand electricity				
Hydro	132 - 289,000	-	16 - 19.3	16 - 19.3
Geothermal	-	-	1.5	1.5
		Total	17.5 - 20.8	17.5 - 20.8
Biomass energy				
Liquids	54,286 - 136,120	8,950,000	66 - 165	66 - 165
		Totals, EJ/yr	251 - 467	98 - 251.5

(1) 10% of fossil fuel generated electricity in IPCC WG III scenarios B2C-MARIA (min) & A1B-Mini-CAM (max).

Slide 15



Slide 16

The Hydrogen Economy – H_2 is a manufactured energy

Today >90% of H_2:

- manufactured from fossil fuels
- >50% by steam reforming of natural gas
- 1 joule H_2 requires 1.5 joules natural gas
- >90% used for chemical processing
- Environmentally friendly H_2 = CO_2 sequestered

- Electrolysis of water – huge facilities for small output
- H_2 manufactured from any source of electricity is equivalent to oil at more than $270 – $540/barrel

Slide 17

Nuclear energy—carbon-free and growing

Nuclear capacity 2003:

- 441 nuclear plants produce electricity in 31 countries
- 33 new nuclear plants under construction in 12 countries
- 19% of electricity in 2001 – same as hydro and natural gas

	1970	1995	2001	2020
Nuclear energy consumption, EJ	1.7	24.6	30.7	31*
Average annual growth rate	11.3%			
Average annual growth rate		3.8%		
World electricity consumption, EJ	15.5	42.5	50.2	79*

- **Limits**: high grade uranium will last 1 to 2 centuries

* EIA projection in International Energy Outlook 2003

Slide 18

Where are we now?– not a *Doomsday* scenario but a *Wake Up Call*

- CO_2 stabilization a difficult task – no simple solutions!
- Conservation – desirable but not a solution
- Efficiency – we need all we can get – only a partial solution
- Renewable energy – too much land – intermittent electricity
- People must adjust to higher CO_2 – energy too vital to turn off the tap
- Large carbon–free energy sources required:
  – to stabilize CO_2 at 550 ppmv
  – to provide adequate future energy
- Possible sources?

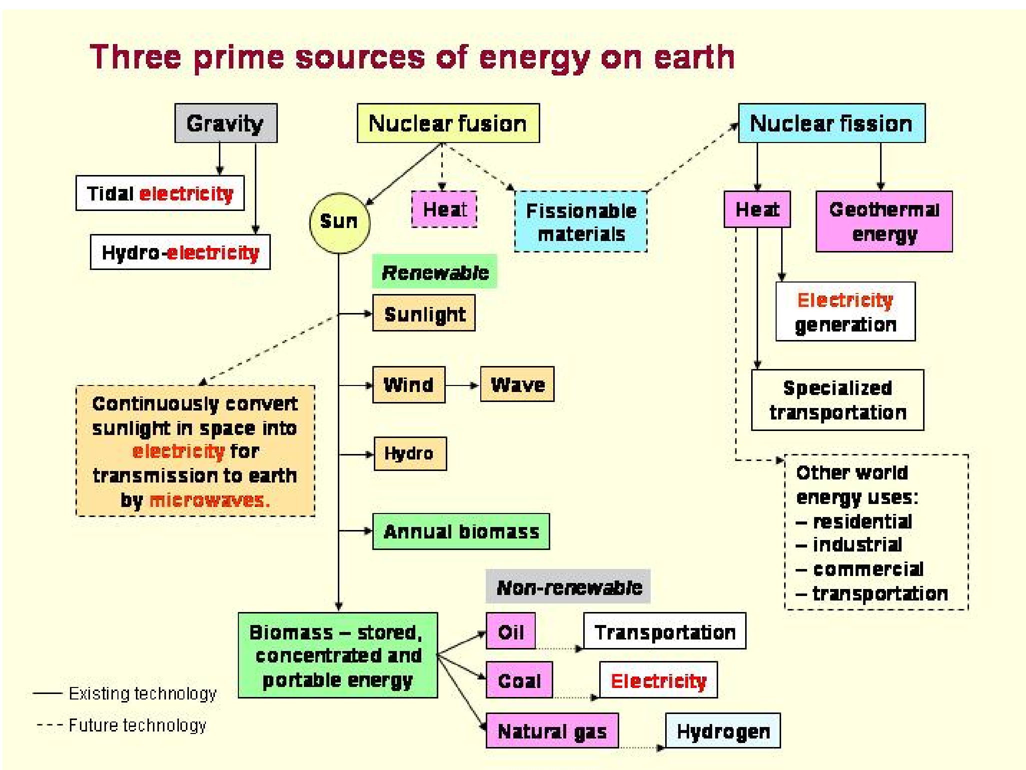
But first . . .

Slide 19

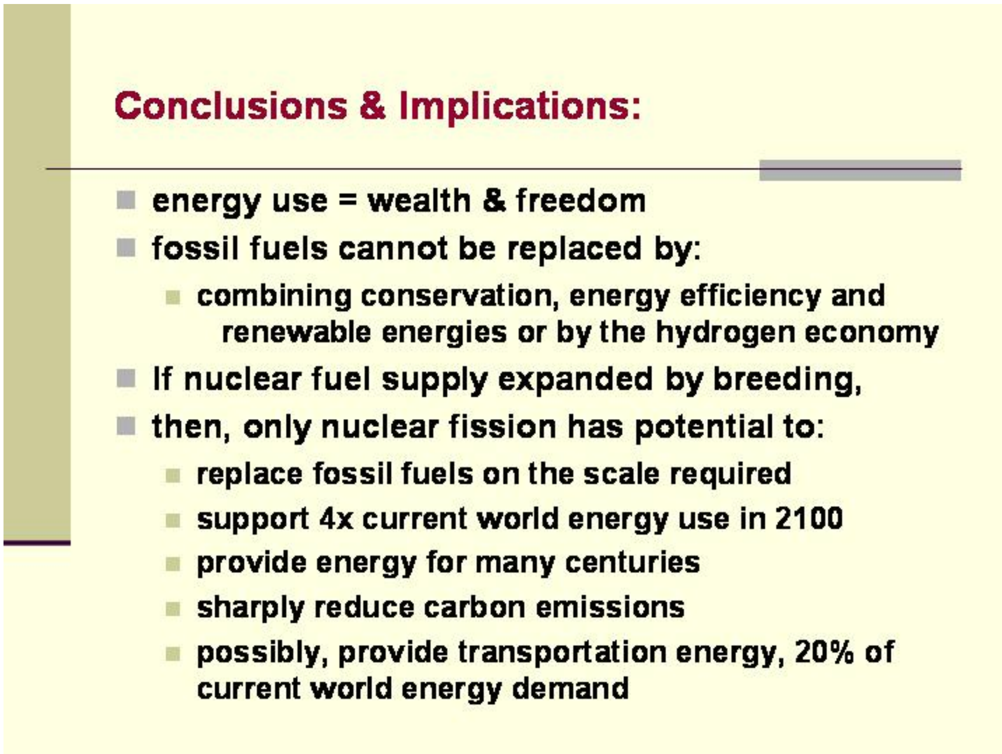
Taxes & subsidies – won't higher fossil fuel prices encourage alternative technologies?

- Discovery and development of new energy sources & technologies requires much more than "*getting energy prices right*"
- No alternatives exist to replace fossil fuels on the scale needed
- Therefore – artificially raising fossil fuel prices before alternatives are available is likely to create unnecessary economic hardships

Slide 20



Slide 21



Slide 22

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