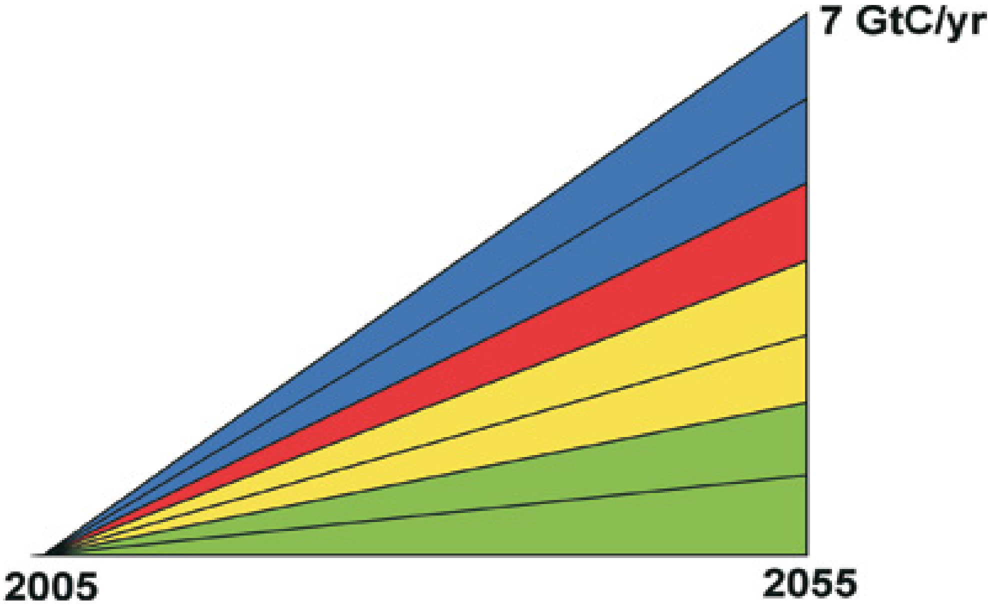
CARBON MITIGATION INITIATIVE



the role of fuel cells

Summary of proposals by
CARBON MITIGATION INITIATIVE
and recommendations by Fuel Cell Power, January 2007
www.princeton.edu www.fuelcellpower.co.uk

FUEL CELLS FOR CARBON MITIGATION

Researchers at the Carbon Mitigation Initiative (CMI) at the University of Princeton, USA have carried out a comprehensive review of the impacts of climate change and recommend measures to stabilize and then to reduce carbon dioxide emissions. During the past 30 years world carbon emissions have grown at an average rate of 1.5% annually, primary energy consumption has grown at 2% and gross world product at 3%. Measures which would reduce carbon emissions are examined. Each 1 gigaton annual reduction of carbon achieved in fifty years time is called a WEDGE **www.princeton.edu**

The goal is to limit the concentration of carbon dioxide in the atmosphere to between 450 and 550 parts per million (ppm) or less than double the pre-industrial concentration of 280ppm. In 2004 the concentration was 375 ppm.

Roughly, this requires stabilization of the present 7 billion tonnes of carbon emissions per year (gigaton carbon/year) till 2054 even though we are on course to more than double this.

If we continue with Business as Usual (BAU) emissions would rise to 14 billion tons carbon per year (GtC/year) in 2054, so we need to displace the additional 7GtC/year with other technologies or lifestyle changes. For this purpose it is assumed that 7 'WEDGES' are introduced, each starting at zero and increasing linearly until it accounts for 1GtC/year of reduced emissions in fifty years time. Each WEDGE must represent new effort, beyond the normal efficiency improvements which would occur under BAU, which is ascertained from historical trends.

Stabilizing then reducing carbon emissions

The selected policies are to be renegotiated periodically to take into account experience with specific wedges and revised estimates of the size of the stabilization triangle. If, for instance, carbon emissions growth increased by 1.8% rather than 1.5% annually then another two wedges would be needed. Stabilization at any level requires that net emissions do not simply remain constant, but eventually drop to zero. After stabilization, a linear decline of about two-thirds will be needed between 2054 and 2104 and R & D must start now to develop the revolutionary technologies required for such large emissions reductions. The review does not cover other greenhouse gases such as nitrous oxide and methane, for which other options are available.

EXAMPLES OF WEDGES

There are three categories for wedges:

- **Efficiency and conservation**
- **De-carbonization of electricity and fuels**
- **Natural sinks**

Each wedge starts at zero and increases linearly until it accounts for 1 gigaton carbon per year (1GtC/y) of reduced carbon emissions by 2054. That is 25GtC reduction per wedge over fifty years. (Note that 1GtC is equivalent to 3.7GtC0_2)

I Efficiency and conservation

The US goal is to decrease carbon intensity (carbon emissions per unit GDP) by 1.96% per year. If this goal were increased by 0.15% per year in every country this would constitute one wedge.

Option 1: double efficiency of cars (light duty vehicles)

About 2 billion cars are projected for 2054, roughly 4 times as many as today, with average 10,000 miles per annum as they do today. One wedge would be achieved if fuel economy increased from projected 30 mpg to 60mpg thereby halving emissions per car of 1tC per annum to 0.5tC per annum.

Option 2: halve vehicle miles travelled

Reduce car use – average annual mileage would be halved from 10,000 to 5,000 miles. Emissions from 2 billion projected cars would be reduced as in option 1 from 2GtC/ year to 1GtC/year.

Option 3: building insulation and renewables

More efficient buildings and renewable strategies like solar water heating could contribute 2 wedges. Approximately one wedge could be achieved from residential and one from commercial buildings. About half of the buildings would be in developing countries.

Option 4: Efficient baseload coal plants,

In 2000 coal power plants with average efficiency of 32% produced 1.7GtC, about a quarter of the total global carbon emissions. 40% efficiency is projected for BAU in 2054. High temperature fuel cells and combining fuel cells and turbines could contribute to the 60% efficiency which would be required to achieve a wedge.

II Decarbonization of electricity and fuels

Option 5: substituting coal power with natural gas

Coal emits about twice as much carbon as natural gas per unit of power output. A wedge would be achieved by displacing 28 GW of new coal power every year with new natural gas power. By 2054 the 1400 GW natural gas power plants would emit 1GtC instead of 2GtC from coal.

Option 6: Capture C02 at baseload power plant

Carbon capture and storage (CCS) technology prevents about 90% of the fossil carbon from reaching the atmosphere but study is needed to understand long term storage security and leakage. A wedge would be provided by the installation of CCS at 800 GW of coal plants by 2054 or 1600 GW of baseload natural gas plants. The likely approach is two steps, the pre-combustion separation of C02 and hydrogen with the latter burned to produce electricity. Then geologic storage of C02.

If gasification rather than steam power becomes established as the power conversion system of choice, then the incremental cost of C02 capture in power production will be relatively low. Technologies for carbon capture are similar to those used to produce hydrogen from coal or natural gas. It is possible that pollutants like sulphur could be disposed of alongside the C02, in a process called co-capture and co-storage.

Option 7: substitute coal with nuclear power

A wedge could be achieved by displacing 700 GW coal or 1400GW natural gas. This would require a tripling of the present nuclear power output and the current challenge of nuclear waste disposal would also grow by a factor of three.

Option 8 substituting wind and other renewables for coal power

As in Option 7, a wedge could be achieved by displacing 700 GW coal or 1400GW natural gas. The list of renewable power sources is long, including hydropower, solar, wind, waves and tides. The capacity of intermittent renewable energy to displace fossil fuel power depends on the availability of stand-alone storage and hybrid storage, such as compressed–air wind-energy storage for remote wind farms. A typical capacity factor for wind and PV is now 25% and this is expected to be 30% in 2054. If displacing coal power, 2000 gigawatt peak (GWp) of wind or PV power would constitute a wedge and 4000 GWp if it were displacing natural gas.

Option 9: PV power for coal power

As in options 7 and 8, a wedge could be achieved by displacing 700 GW coal or 1400GW natural gas generating capacity with photovoltaic power.

Option 10: C02 capture at H2 Plant (see Option 6)

Current production of hydrogen from fossil fuels is 40 million tonnes per year which emits 100MtC/year. Ten times this production would constitute a wedge if the C02 which is at present vented to the atmosphere were stored.

Such centralized hydrogen production would require a hydrogen infrastructure for dispersed users which could compete with small-scale hydrogen production from two already existing infrastructures: the electricity grid with small electrolyzers and the natural gas infrastructure that facilitates local hydrogen production in small reformers.

Option 11: Capturing C02 at coal-to-synfuel plants

It is likely that as oil supplies decline, synthetic fuels (synfuels) from coal and other sources will be used in small units in buildings and to power vehicles. When synfuels are produced from coal, about half the C02 is released and could be stored and the other half remains in the fuel. A wedge would be achieved if about a third of the world's oil were displaced by synfuels and the C02 released during synfuel production were captured and stored.

Option 12: substituting gasoline with hydrogen from wind

Four million 1 megawatt peak (MWp) windmills or four hundred million 10 kilowatt peak (KWp) photovoltaic arrays, operating at 30% capacity factor, would be required to provide the renewable electricity to displace a wedge of carbon from vehicle tailpipes.

Option 13 : Biofuels

A hectare of land used to produce biofuels can have a larger effect on the atmospheric carbon balance than that used as a carbon sink. Most of the new carbon fixed by vegetation each year is allocated to construct short-lived and fast decomposing tissue, such as leaves and fine roots and its capacity to store carbon eventually saturates. A hectare of land can produce biofuels indefinitely.

About a sixth of present cropland would be needed for a wedge, not including fossil fuel inputs. If biomass is co-fired with coal and then the carbon is captured and stored, the process will remove C02 from the atmosphere.

III NATURAL SINKS

Ocean and terrestrial sinks have slowed global warming by absorbing more than half of the carbon that has been emitted into the atmosphere since the start of the Industrial Revolution. For the next 50 years the ability of the ocean sink to store carbon is uncertain by two wedges either way. Climate change could weaken the ocean sink, because solubility of C02 decreases as the ocean temperature increases. In the long term increasing acidity caused by absorption of C02 will also affect the oceans' ability to absorb more C02. The continual upwelling of deep water with pre-industrial C02 concentrations will enable the ocean to continue as a significant sink but if the thermohaline circulation (of which the Gulf Stream is a part) slows down this could reduce the transfer of C02 rich cold water to lower levels of the ocean. On the other hand, for the past twenty years the ocean has been absorbing almost two billion tons of carbon per year at an ever increasing rate and if carbon emissions are stabilised the ocean could continue to absorb an increasing amount of C02 from the atmosphere for up to 50 years. The land sink is very uncertain and could be plus or minus two wedges.

Option 14: Forest management:

The world's 1.5 billion hectares (ha) of tropical forests contain 7-10 wedges worth of carbon in living trees and another 5-9 wedges in soils. The rate of deforestation is not clear, but estimates of the loss of the carbon sink range from 1 to 2 GtC/year. When primary forest is converted to permanent cropland all of the 120-165tC/ha in living trees and up to one third of the 83-150tC/ha in the top metre of soil is emitted to the atmosphere. The conversion of forests to pasture emits the carbon stored in the trees to the atmosphere, but may increase soil carbon by up to 10%. Relative to BAU, half to one wedge could be achieved by the elimination of tropical deforestation by 2054**.**

Option 15 Soil management strategies

It is estimated that man has over time added about 55 GtC to the atmosphere by the creation of 1600 million hectares of cropland. Conservation tillage practices that reduce aeration of the soil could at a conservative estimate contribute a wedge if it were applied to all cropland.

Fuel Cell Power recommends where fuel cells could contribute

I Efficiency and conservation

OPTION 1: double efficiency of cars

According to a report by LBST on behalf of motor manufacturers and oil companies, the substitution of advanced petrol engine cars with fuel cell cars powered by hydrogen from wind energy would reduce primary energy consumption by a third. Carbon emissions would be negligible so the substitution of 1 billion petrol engine cars would constitute a wedge. www.lbst.de

OPTION 3: building insulation and renewables

Several fuel cell manufacturers are starting to provide solid oxide fuel cells (SOFC) which generate 1 kilowatt electricity plus heat at about 85% efficiency from natural gas in commercial and residential buildings. www.cfcl.com.au www.cerespower.com www.hexis.com

Hydrogen fuel cells have the potential to act as load levellers, storing intermittent supplies of electricity from micro wind and solar panels. There are several manufacturers of small proton exchange membrane (PEM) fuel cells and alkaline fuel cells. Energy management systems are being developed which will ensure optimum use of the power and heat generated. Surplus energy may be stored in cars for local journeys or, when cheaper electrolysers become available, as hydrogen for fuel cell CHP units or to power vehicles. Additional power may be imported from the grid or gas pipelines.
www.intelligent-energy-com www.plugpower.com www.ballardpowersystems.com www.cenergie.com

OPTION 4: efficient base load coal plants

FuelCell Energy is developing its clean coal-fuelled solid oxide fuel cell system which will be about 40% more efficient than today's conventional coal based plant. They are continually making further improvements. At least 90% of the system's carbon dioxide emissions will be captured for environmentally safe disposal. FuelCell Energy's technology will be cost competitive with other base load power generating technologies. www.fce.com

II Decarbonization of electricity and fuels

OPTION 6: Capture C02 at baseload power plant

As in **OPTION 4** above, FuelCell Energy's solid oxide fuel cell system will capture and safely store at least 90% of the system's carbon dioxide emissions.

OPTION 7: Substituting coal with nuclear power

Fuel cells used as load levellers for existing nuclear power stations could increase plant efficiency.

OPTION 8 and OPTION 9: Renewable energy, wind and PV (see OPTION 3)

Fuel cells could act as load levellers and produce energy locally, reducing the need for investment in new electricity infrastructure. This could reduce costs, particularly in developing countries where the electricity supply infrastructure is poor. Stanford University's global wind map indicates that the world has more than enough wind to meet all its energy needs. UK Government data indicated that if all suitable roof space were utilised, photovoltaic panels could provide all the nation's electricity.

OPTION 10: C02 Capture at Hydrogen Plant

Hydrogen comprised over 50% of town gas which was widely used before natural gas became available. It may again become economic to transport hydrogen by pipeline, particularly where natural gas is not available.

OPTION 11 Capturing C02 at coal-to-synfuel plants

Intelligent Energy, the fuel cell and hydrogen generating development company, has developed and demonstrated its Hestia hydrogen generation technology in conjunction with Sasol in South Africa.

Hestia is a compact, highly efficient system, which has been run on Sasol's ultra-clean, low-sulphur Fisher-Tropsch diesel fuel produced from coal or natural gas, but it can also use many other fuels to produce its high-purity hydrogen product gas, so that it is capable of serving a broad range of future markets and applications. The hydrogen generated by the Hestia system is sufficient to produce 10kW of electricity, when used with Intelligent Energy's own stationary combined heat and power fuel cell systems. The Hestia platform could also possibly be used for transportation applications, as a refuelling station for hydrogen-fuelled vehicles, for example. With safe, low-pressure metal hydride storage technology integrated into the process, Intelligent Energy has demonstrated near-instantaneous fuel cell system start-up and smooth load-following capabilities.
www.intelligent-energy.com

OPTION 12: substituting gasoline with hydrogen from wind (see OPTION 1)

The CMI proposals are based upon energy being supplied mainly by the existing infrastructures, with electricity from the centralized grid, heat supplied by gas pipelines and transport continuing to be fuelled mainly from oil. We envisage that these three separate infrastructures will gradually merge together, with local generation of heat and power and batteries and hydrogen fuel cells acting as load levellers and powering local transport.

Many people's local transport needs could already be met with battery electric cars powered by renewable electricity. A 600W wind energy collector designed to operate efficiently in variable wind speeds and directions could provide over 1000kWh per annum at 25% capacity. This would be sufficient for 3,000 kms local driving per annum. A solar PV panel would provide sufficient electricity for a similar range. The CMI projection of four hundred million 10kWp solar PV arrays providing hydrogen for two billion cars assumes that a 2kWp system would provide hydrogen for 10,000 mile range per annum for each vehicle.

If half of car owners generated their own renewable fuels to power local driving and used public transport for longer journeys, this would constitute a wedge. Good integrated public transport infrastructures will be needed, preferably built around energy efficient rail and hybrid fuel cell powered tram systems. There would be particular benefits in developing countries which do not have an extensive road infrastructure.

More wind turbines would be required to displace the carbon emissions of the transport sector than to displace the emissions of coal fired power stations because coal has a higher carbon content per unit of power output than either petrol or diesel. If the stations were gas fired the wind turbines would not displace so much carbon. A report in the UK found that wind turbines would be likely to displace Combined Cycle Gas Turbines (CCGT) rather than coal fired stations and in this case the wind turbines would displace no more carbon emissions than they would in the transport sector.

Although there are losses in the production of hydrogen for transport, Daimler Chrysler report that the hydrogen fuel cell drive system is nearly twice as efficient as the most advanced internal combustion engine. A study undertaken by LBST GmbH found that hydrogen fuel cell powered vehicles would be the most efficient future alternative. Further development is needed, but Prof H Wendt gave the efficiency of electrolysis in the region of 75% based upon fuel content or lower heating value (LHV) and estimated that future efficiency would be in the region of 90% (LHV).

III NATURAL SINKS

During the past year, there has been further evidence of increased acceleration of global warming due to 'feedbacks'. Although it is hoped that the recent temperature increase in the Arctic and the acceleration of melting of the Greenland and West Antarctic ice sheets may be partly due to natural fluctuations, it appears that the underlying temperature change is upwards. Possible feedbacks are the albedo effect when ice melts and more sunlight is absorbed; forests becoming net emitters as temperatures rise; the albedo effect when new northern forest plantations absorb more solar radiation; methane hydrates found in shallower water where they warm more quickly and give off C02 at an increasing rate; and increases in water vapour. This year the first comprehensive measurements were taken of the thermohaline circulation which indicated a 10% slowdown. If this continued it could reduce the oceans' capacity to absorb carbon dioxide. However, if carbon emissions are stabilized, the oceans may continue to absorb increasing amounts of carbon for 50 years.

The Global Carbon Project recently reported that carbon dioxide emissions are now rising at 2.5% per year. If this continues, based upon the additional 2 wedges required for change to 1.8% from 1.5% increase in global carbon emissions, at least six more wedges would be required for stabilization. Reports indicate that the permafrost is beginning to melt and if this continues it could add more carbon to the atmosphere than the present annual emissions from fossil fuels. It would require deep cuts in present carbon emissions to achieve stabilization. The use of efficient, low carbon fuel cells now would help to obviate such feedbacks.

OPTIONS 13 and 15 : Biofuels and Soil Management

Based upon ten years research at the University of Minnesota, biofuels derived from low - input high-diversity (LIHD) mixtures of native grassland perennials can provide more usable energy and greater greenhouse gas reductions than other energy crops. LIHD biomass converted into synfuels and electricity via integrated gasification and combined cycle technology with Fischer-Tropsch synthesis (IGCC-FT) yields 50% more usable energy per hectare from degraded infertile land than corn grain ethanol does from fertile soils. During ten year's evaluation, the LIHD biofuels were carbon negative, removing and sequestering more atmospheric C02 than was released from fossil fuel combustion during agriculture, transportation and processing. If degraded land throughout the world were used to grow LIHD biomass, this could potentially provide via IGCC-FT about 13% of global petroleum for transport and 19% of global electricity. Without including ecosystem C02 sequestration, this could eliminate 15% of current C02 emissions, providing one of the seven wedges needed to stabilize global C02. www.umn.edu

The use of energy from household waste will reduce emissions from landfill sites. Energy can also be extracted from agricultural waste and still leave the essential ingredients of fertilisers, that is phosphorous, potassium and nitrogen. Agrilec SARL in France is using alkaline fuel cells from Cenergie Plc to produce electricity and heat from agricultural waste and energy crops. Agrilec's technology will help to reduce the emissions of methane which would otherwise be released into the atmosphere from agricultural waste and has potential in both developed and developing countries. Intelligent Energy's Hestia technology may also be used to generate hydrogen from biomass. (see **OPTION 11**) For larger scale electricity generation, FuelCell Energy's Direct FuelCell can be powered by biogas.