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THE NEED FOR CARBON DIOXIDE DISPOSAL: A THREAT AND AN OPPORTUNITY

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ABSTRACT

Ready energy is a cornerstone of modern society. The policies outlined at the recent Kyoto conference have put in question the largest, most readily available and most cost-effective energy resource available. Even if a doubling of atmospheric CO₂ is deemed acceptable, emission reductions worldwide would have to be drastic. For 10 billion people to share equally into the 1990 emission level would allow a per capita emission of 10% of the current US level. Substantial reductions in CO₂ emissions to the atmosphere are unavoidable. Uncertain is the time available to accomplish this reduction. There are also reasons to be optimistic about the future of coal and other fossil fuels. Barring a surprise technological breakthrough in alternative energies, fossil energy consumption is bound to grow. Political and economic drivers even stronger than the threat of climate change favor economic growth and therefore increased energy consumption. To resolve this apparent contradiction requires new technologies that prevent CO₂ generated by combustion from entering the atmosphere. We will outline available technologies and show how the coal industry can adapt to them.

INTRODUCTION

Ready available energy is a cornerstone of modern society. Nevertheless, the policies outlined at the recent Kyoto conference aim for severe limitations on worldwide CO₂ emissions. This puts in question the largest, most readily available and most cost-effective energy resource that has ever been available to mankind. The purpose of this paper is to show that fossil energy and in particular coal can stay competitive even if severe reductions in CO₂ emissions are mandated. Collection and disposal of CO₂ from combustion processes are technically and economically feasible. CO₂ disposal provides the only known path to a stable energy supply for the future. We also point towards business opportunities for the coal industry that take advantage of the fact that CO₂ emissions from coal tend to be concentrated in large stationary sources. Carbon management at concentrated sources can be made much more cost effective than for a myriad highly distributed and mobile sources.

One does not have to subscribe to the most dire forecasts to see that substantial reductions in CO₂ emissions to the atmosphere will become unavoidable. Hardly anybody considers a doubling or tripling of atmospheric CO₂ levels as acceptable. Yet, preventing CO₂ levels from climbing past twice the natural level will require substantial emission reductions. The difference between holding current levels or letting the level of CO₂ in the atmosphere double is not so much in the severity of the required cut-backs but in the time available to accomplish them. However, in either case new technologies for carbon management need to be developed today and their implementation needs to start soon.
In spite of this real threat to fossil energy, there are also plenty of reasons for optimism. Barring unexpected technological breakthroughs in alternative energies, fossil energy consumption is likely to grow not shrink. Political and economic drivers even stronger than the threat of climate change favor worldwide economic growth and increased energy consumption. At the same time, the political pressure to deal with the environmental consequences will gradually force the introduction of technologies that prevent combustion CO₂ from accumulating in the atmosphere. Generically we refer to them as sequestration technologies.

Sequestration is an important concept because it removes the one obstacle that could stop fossil fuels. With cost-effective sequestration technology available, fossil energy will remain a major competitor in the growing world energy market. Fossil energy is plentiful and will not run out in the foreseeable future. It is cost-effective and proven on the vast scale of world energy demand.

**THE CASE FOR CARBON DIOXIDE EMISSION CONTROLS**

Public concern over environmental issues has grown over the last few decades. In part this concern is due to worldwide economic growth which raises the level of pollution unless unit processes are held to higher standards. It also reflects a higher standard of living that allows society to pay for improved quality of life in the form of more stringent pollution limits. Power plant operators have greatly reduced emissions of NOₓ, SOₓ and other pollutants. Novel technologies have been very successful, while overall energy costs have come down. In the past, limits on CO₂ emissions were not seriously considered, but political events have changed this. Legally binding CO₂ emission limits are undoubtedly going to be introduced and the industry will need to consider how to respond.

CO₂ emission control is different from NOₓ or SOₓ control. Since CO₂ is the major combustion product, the size of the problem is much larger. Furthermore, CO₂ has a long residence time in the atmosphere. Thus, much more time is required to plan ahead. It is not only today's emission rates, but the sum of all previous emissions that matter. Nevertheless, since the residence time is finite there is a sustainable rate of emissions for a given level of atmospheric CO₂. Holding the current emission level, or coming back to it in the foreseeable future, would lead eventually to a doubling of the CO₂ in the air. Politically, it will be very difficult to make a convincing case that CO₂ levels should be allowed to rise past a doubling of the natural level.

Quantifying the risk of increased atmospheric CO₂ is difficult and would go beyond the scope of this paper. A few remarks why CO₂ may be a problem must suffice. CO₂ is a greenhouse gas. This is undisputed and has been known since the early 1800s. The atmosphere is transparent to visible light from the sun which heats the ground. CO₂, among other gases, traps the heat that is reradiated from the ground in the infrared. This insulation, like glass panes in a greenhouse, raises the planet’s temperature. Without CO₂ the Earth would be permanently frozen.

Without question, the use of fossil energy has raised the level of CO₂ in the atmosphere by roughly 30%. This change far exceeds natural fluctuations during the last few thousand years. Since 1800, the CO₂ content of the atmosphere has risen from a stable level of 280 ppm to about 365 ppm today. The steady increase tracks economic growth.

It is easy to calculate the heat trapped by CO₂ while holding all other parameters fixed, but predicting the actual response of the climate is not. The climate fluctuates even without CO₂ forcing, and the observed rise in temperature does not track the rise in CO₂ very closely. Nevertheless, the IPCC, an international technical committee, has stated that human influence on
the climate is already discernible. Secondary effects, like a rise in ocean levels, are even harder to predict and it is even more difficult to prove a causal connection with atmospheric CO₂.

Carbon dioxide also plays an important role in supporting life on Earth. CO₂ affects the rate of photosynthesis. It affects the relative advantages of different plant species. CO₂ is also involved in the formation of calcium carbonate in bones, shells and coral reefs. Blood pH and breathing are largely controlled by CO₂. The physiological importance of CO₂ suggests that large excursions in the atmospheric level could affect ecosystems more directly than just through climate change.

What increase in the level of CO₂ could or should be tolerated is a value judgment that ultimately is performed by the political process. A political trend towards limiting CO₂ emissions has emerged. It is supported by international consensus which found its expression in the UN conferences from Rio de Janeiro to Kyoto. While it is hard to predict the precise outcome, a consensus that would allow CO₂ levels to rise past twice the natural level appears unlikely. Much more stringent levels have their advocates, but are probably impossible to achieve. Already the industry faces a high likelihood that rules will be enacted to limit US emissions by 2010 to 7% below the 1990 rate. Compared to business as usual, this would require a cutback in CO₂ emissions of about 35% to 40%.

Simple calculations suggest that sustaining a CO₂ level below 560 ppm, which is twice the recent natural level, would require the world to stay below 1990 emission rates. To hold current levels would require a cut-back in emissions by about a factor of three. These numbers follow from an average residence time of 100 to 150 years and are quite uncertain, as a detailed understanding of the sources and sinks and their rate of uptake is still missing. It appears that apart from the ocean, forests in the moderate latitudes are taking up CO₂. At present it is not clear whether some of these sinks will saturate which would require further emission reductions. For a world population of 10 billion to share equally into the 1990 emission rate would require the US to cut back by 90% of its current per capita emission rate. To hold a level of 350 ppm would require another reduction by an additional factor of three. Whether one considers a 90% or 97% reduction, either one requires a fundamental change in the energy market.

A limit around 560 ppm of atmospheric CO₂, which is 200 ppm above the current level, would allow for some time during which emission rates could keep growing. However, eventually emissions would have to come down to 1990 levels. The current rate of growth of the CO₂ level in the atmosphere is nearly 2 ppm per year, but worldwide economic growth is rapid and is likely to cut the buffer down to maybe 50 years. Power plants in the planning stages today should still be in operation by the year 2050. Thus, now is the time to consider a plan of action.

**Fossil Has Future**

In discussions concerning the fate of fossil energy, pessimists often implicitly assume that even without the additional problem of global warming, fossil energy will gradually lose its importance because resources are dwindling and alternative energy is getting cheaper. Given this outlook, the theory goes, one should accelerate the phase-out in order to reduce greenhouse gas emissions. A carbon tax, for example, might accelerate the transition. We disagree with such a pessimistic outlook which has been proven wrong in the past. We argue that resource availability, the lack of serious competitors, and the likelihood of substantial growth in world energy demand will almost guarantee an important role for fossil energy throughout the next century.
Resource Availability

So far improved technology has easily kept pace with any increase in difficulty in the extraction of fossil fuels. Energy is cheaper today than it was 50 or 100 years ago. In oil and gas exploration one may see a trend to more remote and deeper wells, but even this is partly explained by an increase in the average size of reservoirs. For coal there is no obvious increase in the level of difficulty in mining and the estimates of the reserves are huge. World coal resources are estimated at 10,000 Gt or more. This number should be compared to today's annual consumption of 6 Gt of carbon in all fossil fuels combined. Proven reserves are smaller but even these would last many hundred years at current consumption. Oil and gas reserves although smaller than coal reserves have held remarkably constant over the years. If one includes oil shale, shale sands and methane hydrate reserves, resources become virtually inexhaustible. Estimates of methane hydrates reach as high as 4×10^6 Gt of carbon. Since the atmosphere contains only 10^6 Gt of oxygen, this would suggest that the limiting resource is oxygen not carbon.

To view the various fossil energy sources in aggregate is justified, since interchanging the various fossil energy forms is not very difficult. With the advent of "designer fuels" in which carbon chains are reworked completely, the relative advantage of one raw resource over another diminishes. The South African coal liquefaction plants (SASOL process) have shown that the economic threshold for converting coal to oil is quite low. Thus, even if one form of fossil energy were to run out, the remaining ones could clearly fill the gap.

It appears to be a safe bet that technological advances over the next 50 years will easily maintain the cost of the resource extraction at current or even lower levels. Resource limitations are not likely to be an important obstacle to the use of fossil energy.

Alternative Energy

Alternative energy, if cheap, could put fossil energy out of business. The introduction of the automobile, the airplane, television and the personal computer show how rapidly and thoroughly a new technology with a strong economic advantage can take over. However, before one bets on alternative energy, one should carefully consider the potential of the likely contenders. Ignoring dark horses like fusion, the main competitors to fossil energy are solar and wind energy, biomass, geothermal, hydroelectric and nuclear energy. The need to control greenhouse gas emissions will give these alternatives an economic boost but we consider it too small to tip the balance.

Solar electricity will become cheaper than it is today (ca $0.12–$0.25/kWh) but it is very far from a competitive level of 3 to 5 cents. If solar energy is to satisfy more than peak demand another costly layer of infrastructure for energy storage would have to be added. Wind energy, which in good sites is cheaper than solar energy, is limited by the availability of good locations. Hydroelectric energy which is very cost-effective and geothermal energy are similarly limited.

The fundamental disadvantage of wind and especially solar energy is the dilute nature of the energy source. Dilute sources are intrinsically costly and the large use of land is a major environmental consideration. To collect an average of 1 kW from sunlight, one needs at least 20 m^2 of land. Even for the most simple stationary systems this would imply a mass in excess of 200 kg. Hydrocarbon driven car engines can easily get 100 kW from a comparable weight. By requiring a less massive plant, fossil energy has a fundamental cost advantage.

Biomass production has been suggested and tried. In an environment of falling energy prices it is simply not competitive. This can be seen comparing commercial crops with a future fuel crop. Intensive agriculture can yield on the order of 20 t/ha of dry mass. This is roughly equivalent to
15 tons of coal. Thus a hectare of land (~2.5 acres) could yield a crop that corresponds to $300 of coal. Typically, a farmer can expect returns on the order of $700 to $800 on a hectare. The comparison is still overly optimistic because it leaves out the substantial economic and energy cost of processing, e.g. drying, the plant material. Thus, the inherent inefficiency of photosynthesis which collects 1% to 3% of solar input makes it virtually impossible for biomass to compete with fossil energy.

Nuclear energy is close enough in price to be a major competitor. Herzog et al. estimate that nuclear energy would add a cost of about $13 to $61 per ton of avoided CO2 to the cost of electricity. The difficulty faced by the nuclear industry seems to be a combination of cost and public perception. Nuclear waste disposal is generally considered a serious political issue. Proliferation of nuclear technology and nuclear materials is another major issue that deserves consideration. The current policy of discouraging the use of fossil fuels raises the risk of proliferation, as developing and politically unstable countries are driven towards nuclear energy.

On a price basis fossil fuels are likely to remain strong competitors. With deregulation arriving in the US and the rest of the world, coal energy is bound to get cheaper. New technologies like high temperature turbines have the potential of reducing cost. Future cost reductions in power production would only continue the trend of the last 20 years which has already proven the pessimists wrong.

Energy Demand and Energy Efficiency

Energy demand is mainly fueled by economic and population growth throughout the developing countries. Rapid economic growth in these countries is highly desirable politically, as it provides for political stability. Economic growth appears to be the only way of slowing down and stopping the world's explosive population growth. The empirical correlation between economic development and a reduction in population growth is well established. Economic growth in turn is tightly linked to increased energy generation. Thus, ample low cost energy is critical for the political future of the world. Fortunately, trends over the last two decades have been pointing in the right direction. As a result energy demand in the developing countries is growing rapidly. The last decade has seen sustained growth in many Asian countries around 8% annually.

Improved efficiency in power production and in the use of energy could reduce the demand by a small amount. Energy will be saved, if the cost of reducing energy use is less than the cost of energy itself. The large price differential for energy between Europe and the United States provides a measure of how much energy savings could be expected either from raising energy prices or from innovation that makes efficiency more cost-effective. Europe uses energy more sparingly but the difference is small enough to suggest that large energy savings are not easy and that small incremental improvements in technology are not likely to yield large savings. Furthermore, new technologies not only provide for increased energy efficiencies, they also lower the cost of energy production which raises consumption. New technologies also offer novel ways of consuming energy or ways that used to be too expensive. For this reason alone one can expect energy demand in the industrialized countries to grow as well.

Raising the cost of energy simply to reduce its consumption appears counterproductive. It raises the cost of goods and thus will reduce overall economic output. Since it takes 1 kWh of primary energy to generate 23 cents of GDP, an increase in the cost of a kWh by several cents is bound to put a strong damper on any economy. For the developing countries where world energy consumption grows most rapidly this would be a devastating strategy.
Energy demand will grow dramatically if the world succeeds in providing people everywhere with a decent standard of living. A world of 10 billion people that consumes energy like Europe does today would be consuming 5 times more energy than at present. If consumption rises to America’s level of today, the world would be consuming 10 times as much energy. Provided that the CO₂ emissions are under control, fossil energy is in a prime position to meet the need.

**Sequestration Technologies**

Sequestration technologies prevent CO₂ from accumulating in the atmosphere. This goal can be achieved in a variety of ways. CO₂ is collected either at the point of the combustion or is taken later from the air. The CO₂ that has been collected may be chemically transformed before it is disposed as a waste. It has also been suggested that a fraction might be recycled back into the economy.

Currently, only biomass generation extracts CO₂ from air. No other method has overcome the 1:3000 dilution. Extraction from air would be appealing because it would avoid an entire infrastructure dedicated to the transport of CO₂ and would eliminate the re-engineering of existing combustion processes to include CO₂ separation.

Carbon dioxide can more easily be collected at the point of combustion. It is most easily accomplished at concentrated sources and viable technologies exist, for example chemical scrubbing with MEA or membrane separation techniques. The major hurdle to retrofitting existing power plants is the low concentration of CO₂ in the flue gas which tends to be around 10% to 15%. A more economical approach might start with redesigned power plants. For example, integrating CO₂ collection into an integrated gasifier combined cycle plant is much easier because pressures are higher and the exhaust is much richer in CO₂. In plants that are designed to produce hydrogen, collection of CO₂ comes naturally and is achieved with hardly any incremental cost. The collection of CO₂ is not an insurmountable obstacle to sequestration. Cost estimates vary from an increase by 30% to 40% of electricity costs in retrofits, to very small cost increments for hydrogen producing power plants.

Pipeline technology for transporting carbon dioxide is well understood and costs have been estimated at $10 per ton and 1000 km. There is an operating pipeline that transports CO₂ from a natural reservoir across New Mexico in order to inject it into an oil field under secondary recovery. The Great Plains plant in North Dakota is starting to collect its CO₂ generated in the synfuel process and ship it to Canada for enhanced oil recovery. These examples show that transporting and shipping CO₂ will not stop sequestration.

Once collected, the options for turning CO₂ into valuable products are extremely limited when compared to the volume of CO₂. CO₂ emissions in the US amount to about 20 t per person per year. Not even road construction could absorb such quantities, e.g. as carbonates. Excessive transportation costs would make this option unattractive in any case. Carbon recycling in the form of plastics or other organic compounds is ruled out by its demand for energy which would need to be satisfied by non-fossil sources. The synthesis of nearly all carbon rich products requires substantial amounts of energy usually in excess of what has been extracted at the power plant. The only market of sufficient size into which CO₂ could be recycled, is that of carbon based fuels. To make this work, requires cost-effective, non-fossil energy to recharge the carbon energy carrier. Such an energy resource would be able to replace fossil energy altogether. Its development would amount to a major unexpected breakthrough in alternative energy. Currently the biggest use of CO₂ is for
enhanced oil and gas recovery where it is injected underground. Because of its similarity to underground disposal we will discuss this case below.

We conclude that, while it is feasible to collect CO₂ at concentrated sources and transport it to a site for further processing, there is virtually no market for the resulting product. This is because the use of carbon as fuel dwarfs all other material outputs. Reprocessing CO₂ back to fuel would obviate the need for sequestration as it would herald the advent a new and better energy technology. Thus we are forced to conclude that sequestration must rely on waste disposal rather than reuse. In the following we outline a number of disposal options that have been developed over the last decade. It will become clear that sequestration is already feasible and could start today, even though more work is required before the technology can be applied at full scale.

**Underground Injection**

Injecting CO₂ into geological formations is a disposal option which is already practiced. Motivated by a high carbon tax in Norway, $55/t of CO₂ Statoil re-injects CO₂ stripped from natural gas into an aquifer 1000 m under the sea floor at the Sleipner field in the North Sea. Routinely, CO₂ is injected into oil and gas producing fields to enhance production. A particularly interesting example of gas recovery is from deep coal beds. Coal beds that lie too deep for economic recovery of the coal still contain a large amount of methane which is adsorbed to the coal surface. A potentially very efficient way of extracting this methane is through gas exchange with CO₂ which is adsorbed much more strongly than methane. The CO₂ exchanges places with the adsorbed methane which can then be produced. The CO₂ is fixed in place and remains behind.

**Ocean disposal**

Ocean disposal has been extensively studied. There are various forms which differ in how and where CO₂ is introduced into the ocean. CO₂ is transported in an undersea pipeline from the shore, or it is introduced from a ship that carries it to a deep part of the ocean. CO₂ is introduced as a compressed gas at great depth, or injected as a water clathrate. It can be introduced as dry ice or bubbled into intermediate depth where it dissolves in the water. While still many questions remain, one could consider this option as available on a small scale. Very deep storage has the advantage that the CO₂ becomes denser than water and forms a lake on the bottom of the ocean which only gradually dissolves into the surrounding water.

Ocean circulation guarantees that over time the highly soluble CO₂ is mixed into the ocean as a whole. The allowable change in pH sets an upper limit on how much can be stored in the ocean. Time constants for exchange with the air are estimated between 500 years to a few thousand years. Oceans are a natural sink that is much larger than the atmosphere. In that sense this is an accelerated natural process.

**Biomass Sequestration**

Photosynthesis extracts CO₂ from air to form starch or similar organic materials by adding H₂O and sunlight. There are several ways this process can contribute to the reduction of CO₂ in the air. Biomass can accumulate in standing forests or other green areas. Changing the size of the reservoir is a one time event and according to the agreement of the Kyoto conference should be accounted for in the overall carbon budget. The second approach is to harvest the plant material and sequester it in other forms. For example, construction wood is taken out of circulation but not for more than...
a few decades. Fertilization of the ocean in order to increase biomass production which then sinks to the deep abyss is a direct form of biomass sequestration.35

**Carbonate Disposal**

Contrary to common perception, CO₂ is not the lowest energy state of a carbon atom. The reaction of CO₂ with common mineral oxides to form carbonates like magnesite or calcite is exothermic and thermodynamically favored under ambient conditions. Consequently it is possible to dispose of CO₂ as a solid mineral carbonate.36 The advantage is that the waste product is environmentally safe and thermodynamically stable. Raw materials for binding the CO₂ exist in vast quantities far exceeding even the most optimistic estimates of fossil energy reserves. The reaction is well known to geologists because it occurs spontaneously on geological time scales. It was first suggested for CO₂ disposal in a letter to Nature by Seifritz.37 Over the last few years we have studied this reaction and our work is centered on developing an economically viable above ground process that accelerates the natural reaction rate so that it can be performed cost-effectively.38 Since the reaction generates heat, we aim for an implementation without an external supply of energy.

At present this process is still in an early research phase. Our goal is to achieve a cost of about $20/t of CO₂ but this still needs to be demonstrated. The long term stability of the waste product makes the process appealing.

**CHOOSING A SEQUESTRATION METHOD**

Because of the vast scale at which sequestration needs to be performed it is important to develop criteria to compare new technologies. Here we present such criteria and apply them to the above mentioned disposal methods.39

**Safety**

Any viable method of disposal must be safe. A major concern with large scale disposal of CO₂ in its original chemical form is that under ambient conditions it is a gas. Given a chance, it will escape from storage and revert to its gaseous state. Therefore, it is necessary to maintain indefinitely a physical barrier that prevents the escape of CO₂. Since CO₂ is heavier than air, a sudden release into the atmosphere would cause the gas to flow near the ground and form a blanket that would asphyxiate life. The danger of storing CO₂ has been demonstrated by natural disasters of sudden releases of CO₂. The 1986 outgassing of Lake Nyos, a crater lake in Cameroon, killed 1,700 people. The CO₂ amounts involved were small on the scale of CO₂ disposal. The best estimate40 of 0.1 km³ equals the weekly output of a single gigawatt power plant.

Even slow CO₂ seepage from storage sites could pose a serious hazard if it were to occur in built-up and populated areas. Such seepages are known to occur naturally and people and animals need to be kept away from them. However, natural sources are rare and far smaller than emissions from man made sources.41 Consequently, they do not provide a good estimate of the size of this problem.

In the past storage in caverns has been considered as a possible disposal option.42 The hazard would have been quite large for these methods. In the case of deep underground injections into a porous rock one will have to analyze the hazard on a reservoir by reservoir basis. Sometimes, the depth and stability of the rock formation are beyond question. In some situations the presence of
calcium and magnesium bearing minerals adds the additional assurance that after some time the CO2 will be consumed by forming carbonates and bicarbonates. In other cases, the CO2 which at medium depth floats on the aquifer water will gradually move over large distances and in the end find fissures and high porosity streaks where it can seep back to the surface. Given that for some reservoirs a large number of wells is required to inject the large volumes of CO2, one also needs to consider the integrity of the well head over long periods of time.

Ocean disposal at great depth tends to be hydrodynamically stable because CO2 becomes denser than water. So it is quite different than the situation in Lake Nyos. It would require some mechanism, for example volcanic activity, to drive a CO2 rich plume near the ocean surface.

Carbonates are thermodynamically stable and simply cannot release significant volumes of CO2.

**Environmental Impact**

The overall environmental impact of fossil energy consumption should be kept to a minimum. CO2 disposal must be environmentally more benign than emissions to the air. Most methods of disposal either store CO2 in high concentrations or in diluted form by introducing it into a large reservoir like the ocean or the atmosphere. While dilution avoids the danger of a sudden release, it is hard to rule out wide-spread environmental damage in the long run. This is precisely the issue we are facing today with the greenhouse effect. The high solubility of CO2 in water suggests that even highly concentrated disposal in the ocean will lead to large scale plumes of CO2 that ultimately change the pH of large swaths of ocean water. One should note that the size of these CO2 disposal sites dwarfs any natural CO2 seeps into the ocean.43

Biomass generation requires large land or sea areas simply to collect the necessary sunlight. This by itself implies substantial and large changes in the environment. For intensive agriculture these changes cannot be ignored. Use of fertilizer is already viewed with concern and it would become much more widespread. Eutrophication of the oceans35 for enhanced biomass generation should be compared to the eutrophication of the Great Lakes and the large effort it took to reverse this environmental disaster.

In spite of the fact that carbonate disposal relies on mining additional raw materials its impact is relatively small. The size of the mining operation as measured in terms of surface disturbance is far smaller than an equivalently sized surface coal mine. The end product is a common mineral that also occurs naturally in vast quantities and is known to be environmentally benign. Consequently there is little concern with regard to the overall or long term environmental impact of the waste product. Furthermore, the product is a stable solid and will not leave the area where it has been deposited.

Underground injection also limits the impact to a small site. In those situations where the permanency of the method can be guaranteed the environmental impact is small.

**Legacy problem**

Public perception as well as common sense dictate that any large scale solution to the problem may not pose severe legacy problems for future generations. By these we mean problems that our generation creates in the process of CO2 disposal which will require vigilance or actions by future generations who may not be in a position to deal with the situation forced upon them. The storing of large volumes of CO2 are apt to cause such legacy problems. Ocean disposal and underground injection both heavily rely on computer simulations to assure the safety and permanence of the disposal. Since models tend to be subject to uncertainties, constant monitoring for generations is
likely to be required. Not unlike nuclear waste, large reservoirs of CO\textsubscript{2} would need to be monitored and protected against a sudden CO\textsubscript{2} release or gradual leaks. The cost of guarding and monitoring deep aquifer sites or the progress of plumes under the ocean is likely to be substantial and would fall on future generations.

**Permanence**

The goal of sequestration should be to keep fossil fuels viable. This requires permanent disposal. Any disposal that lets the CO\textsubscript{2} gradually reenter the atmosphere only changes the time history of the emissions, it does not change total emissions. For peak emissions to be substantially reduced, the mean storage time must exceed the anticipated duration of fossil fuel consumption. For example, if current emissions were to be found a factor 2 too high to be sustainable, and if one anticipates another 200 years of fossil fuel consumption at 4 times today's rate, then typical disposal must last at least 1,600 years to avoid laying the seeds for a greenhouse problem caused by CO\textsubscript{2} escaping from leaky disposal sites. Such a greenhouse problem would start within the next two hundred years and would last for the lifetime of the storage.

Storage times for most biomass processes (months to decades) are far too short to consider. Even the quoted numbers for storage in the ocean are marginal (few hundred to a few thousand years). Some aquifer disposal will release a part of the CO\textsubscript{2} back in the atmosphere,\textsuperscript{44} other storage sites, e.g. deep aquifers in Canada, appear more or less permanent. Carbonates because of their thermodynamic stability are stable on geological time scales.

We emphasize that the time constants we consider necessary are much longer than many workers in the field consider sufficient.\textsuperscript{45} The difference is that shorter term disposal is useful if coupled with an immediate phase out of fossil fuels. We doubt that an industry would be willing to heavily invest into a technology whose only purpose is to facilitate its orderly demise.

**Complete Solution**

Considering the rapid rise in world energy demand, technologies are needed that can, at least in principle, reduce atmospheric CO\textsubscript{2} emissions to zero. The reductions ultimately required were estimated above to be in excess of 90\%. For the next 50 years, ocean and deep aquifers provide substantial storage capacity even though the availability varies regionally. If measured against the scale of available hydrocarbons, however, they fall short. Biomass falls short in storage capacity, and – on land – in available collection area. Minerals for carbonate disposal are available far in excess of fossil fuel reserves and there is no concern that they could run out.\textsuperscript{46}

**Economic Viability**

For sequestration to be successful it has to have a lower cost than all other options. The cost of ignoring the problem is hard to judge but will be irrelevant once regulations enforce emission reductions. To set the scale one may compare with the typical cost associated with bad weather. A single large storm or flood can cause damage in the tens of billions of dollars. For the US an annual cost of $30 billion would amount to 1 cent per kWh. Carbon taxes as in Norway may reflect a societal consensus on the value of CO\textsubscript{2} reductions. A tax of $55/t of CO\textsubscript{2} amounts to about 5¢/kWh. Such a high cost probably would render sequestration too expensive when compared with alternative energy sources. A recent MIT study\textsuperscript{22} suggests that there is at present no alternative energy form that could reduce CO\textsubscript{2} emissions on a large scale for less than $20/t of CO\textsubscript{2} avoided.
However, there are a number of options in the $30 to $60 range. For continued use of fossil energy, CO$_2$ disposal costs need to stay below this level.

Costs for the various schemes discussed above are overall quite uncertain but it is clear that under special circumstance they can be quite low. Underground injection if combined with enhanced oil or gas recovery can in some cases be performed at no incremental cost, and in other cases a small credit for CO$_2$ disposal may make enhanced recovery economically viable. On a small scale biomass can be very cost effective, for example reforestation programs, of value by themselves, may come virtually for free. Biomass as byproduct of other agricultural activity can be low cost even though it can never grow to the appropriate size. The large scale options again depend on circumstances. Deep aquifer and ocean disposal costs are estimated between $5 and $15 per ton of CO$_2$. However, see Ref. 47 for much higher cost estimates on ocean disposal. Carbonate disposal is still in an early research state but a goal of $15 to $20 per ton of CO$_2$ appears to be reasonable.

**CONCLUSION**

Even though legally mandated carbon dioxide reductions are almost certain to arrive, fossil energy is in a good position to weather this storm for a number of reasons. First, the technical means to comply with mandated reductions are already available and will be further developed. Second, political and economic drivers even stronger than climate change will provide a continuing and growing demand for energy. Third, vast resource reserves and a lack of strong competitors will assure an important role for fossil fuels in the future energy mix.

Sequestration could start immediately if economic incentives were provided and where circumstances come together in the right way. Deep aquifer disposal is already practiced on a small scale and probably could start rapidly in places like the Midwest or Alberta. Enhanced oil and gas recovery projects or deep coal bed methane projects may provide low cost sequestration. Later, more permanent and inherently safe methods like carbonate disposal will come on line, at which point there is more than enough sequestration potential to provide for the entire economy.

Among the various fuels, coal is affected most directly because it is the most carbon intensive fuel, i.e., it generates the most CO$_2$ per unit of heat. This is a fact of thermodynamics which no form of chemical processing can change. Improvements only come from increased efficiency which reduces the required thermal input and from sequestration which eliminates the undesirable impact of the CO$_2$. Natural gas is the least affected, because it is the least carbon intensive of the fossil fuels. However, one needs to include in this comparison the CO$_2$ that is commonly stripped from natural gas at the well head. The advantage of a lower carbon content of natural gas suggests that the competition between coal and natural gas is going to be more fierce than it has been in the past.

For CO$_2$ reductions to accomplish anything they will have to be substantial, at which point they will affect all fossil fuels. An important consideration for coal is to avoid a short term policy that relies on fuel switching. Due to the lower carbon intensity of natural gas, a minor reduction in CO$_2$ emissions can be accomplished by replacing coal with natural gas. In fighting rear guard actions against the introduction of carbon dioxide reductions one plays into the hand of natural gas. The likely outcome of such posturing is a compromise policy of small reductions that could be most easily accomplished by fuel switching.

Coal has two major advantages in the short term: (1) coal is intrinsically cheaper than oil and gas, (2) coal's niche is at the large scale power plants. If natural gas is also subject to sequestration, it loses the competitive edge that comes from deploying many small units as decarbonizing implies a
centralized facility. Coal plants need to raise efficiency and this probably will mean a transition away from pulverized coal combustion to the generation of high quality fuels, like synthesis gas or even hydrogen. If such plants were marginally economic prior to sequestration with sequestration they will have a clear advantage. In feeding a distributed system of gas turbines with hydrogen or a hydrogen enriched synthesis gas, coal could well compete on a cost basis with natural gas if natural gas also must go through decarbonization.

Large scale plants have the advantage of easy access to waste CO\textsubscript{2}. Coal in particular, in an environment of allowances or credits could add to its business by collecting far more CO\textsubscript{2} than it needs to remove for its own operation and a power plant operator could add to profits by selling credits or allowances to the oil refining industry which will have a very hard time in collecting waste CO\textsubscript{2} from automobiles.

A political climate in which emission credits are sold is probably the best for coal. Under those conditions coal can keep operating and even profit from selling credits. By virtue of its large scale availability and low production cost, coal could provide carbon free energy in the form hydrogen and electricity to its customers.\textsuperscript{50} The CO\textsubscript{2} produced could be sequestered permanently and safely. Thus coal could become a zero-emission power producer.

\textbf{List of References}


