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Title: A REVIEW OF EMERGING TECHNOLOGIES FOR
SUSTAINABLE USE OF COAL FOR POWER GENERATION

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A review of emerging technologies for sustainable use of coal for power generation

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ABSTRACT: Concerns about climate change and environmental consequences of increased levels of atmospheric CO_2 will require the power generation industry to reduce CO_2 emissions from current levels. Unfortunately, for reductions to have the desired effect they will have to be large. While the schedule of the Kyoto Protocol may appear daunting, in the long term mere compliance with the protocol will hardly change the rate of increase of atmospheric CO_2. There are, however, technical, economical and practical choices that will allow the industry to meet the requirements of the protocol and ultimately stop the increase in atmospheric CO_2 without eliminating coal from the fuel mix. In this paper, we present a review of current and emerging technologies for CO_2 sequestration. We provide a summary of the underlying scientific principles and discuss the practical and economic aspects of sequestration technologies, which will allow continuing use of global coal resources with minimum or no impact on CO_2 levels in the atmosphere.

1 INTRODUCTION

In this paper, we focus on coal as a major source of energy and emerging technologies that will allow coal to be used in power generation with minimal or no accumulation of CO_2 in the atmosphere. The problem of continuously increasing the CO_2 content of the Earth's atmosphere requires solutions, which will allow sustainable power generation at increased levels. Within the last few years the consensus has been steadily growing, that excess carbon dioxide will cause a significant change in climate that will have repercussions on a wide variety of human activities. Most predictions are, however, based on complex climate models that still cannot fully capture all the physical effects that interact in leading to a change of climate. Consequently, there remains a considerable amount of uncertainty.

The carbon dioxide content of the atmosphere has increased dramatically since the beginning of the 19th century. It has risen by about 30%, from 280 ppm to 360 ppm. This change is well documented (Siegenthaler & Oescher, 1987, Keeling et al., 1995). The increase recorded during the last 40 years (from 315 ppm to 360 ppm) accounts for more than 50% of the total increase during the last two centuries. The general consensus is such that the increase of CO_2 in the atmosphere is due to human activities, primarily the combustion of fossil fuels. It has been pointed out (Keeling *et al.*, 1995) that the rate of increase closely tracks the growth in the generation of CO_2 from fossil fuels and cement production. At present, about 60% of the CO_2 thus generated remains in the atmosphere. The 6 Gt of carbon that are emitted annually (EIA, 1998) amount to 1% of the 570 Gt of carbon that naturally would reside in the atmosphere as CO_2.

It has also been shown that the change of atmospheric carbon dioxide is accompanied by a corresponding drop in the atmosphere's oxygen level, which implicates combustion processes, rather than, for example, a decrease in the rate of photosynthesis, which would also increase CO_2 levels. Furthermore, precision measurements of concentration gradients in CO_2 and O_2 point to the Northern Hemisphere as the source of the excess CO_2 (Keeling et al., 1996). Considering the current and projected future fossil carbon consumption and the available fossil carbon resources, it is conceivable that in the distant future the rate limiting resource is oxygen from the air rather than fossil carbon from the ground. Long before this point is reached, CO_2 levels would have reached intolerable levels. Thus, CO_2 sequestration is an important step to maintain access to fossil fuels for centuries to come.

Here, we are not concerned with the straightforward approach of avoiding CO_2 production by either foregoing energy production or by using other forms of energy. These methods can and will contribute to the reduction of CO_2 emissions. Nevertheless, energy conservation and energy efficiency will fall far short from what would be required. Alternative

forms of energy that don't produce CO_2 are currently far too expensive to compete. Unless there is a major and unexpected technological breakthrough for a carbon free energy resource, one cannot expect to remove the largest contributor to today's energy mix from a growing world energy market.

2 COAL'S STRENGTH

Among raw energy resources, coal is a strong competitor. Coal is available on every continent and in virtually every country. Mining technologies are well advanced and coal has by far the lowest cost of all fossil fuels. However, energy extraction from coal requires processing which adds to the cost. Energy needs to be put in the form of electricity or in the form of chemical energy carriers that could be readily distributed and consumed without undue environmental impact. The low price of coal allows for substantially more processing than would be acceptable for crude oil or raw natural gas.

As chemical energy carriers become more distinct from the raw resources, raw resources become interchangeable. For electricity the transition to interchangeable energy sources has already occurred. Electricity is generated from oil, gas and coal as well as from non-fossil sources. Local conditions prevailing at a particular time determine which resource is cheapest and will be used. Coal is not a likely source of gasoline or natural gas, as they are too close to crude oil and raw natural gas, respectively. Among the energy carriers contemplated for the future, the most prominent is hydrogen. Methanol also may find use in the transportation sector. Both are sufficiently different from all raw energy resources that their production from coal could be considered. The higher processing cost must be offset by the much lower cost of coal.

Managing the carbon cycle is made easier if the energy is distributed in a carbon free format, for example as hydrogen or as electricity. For carbon based energy carriers a solution needs to be found that can recover carbon at the end of the distribution chain, or one needs to look at other sources of carbon that are sequestered instead.

Hydrogen production from coal would transfer the energy that is stored in coal into a clean hydrogen gas that is most likely derived from reducing water. In transferring the oxygen that is attached to hydrogen to carbon, one transfers the energy from a carbon-based carrier to hydrogen.

3 SUSTAINABLE COAL

Sustainability is usually claimed by technologies relying on renewable resources. However, sustainability or a state near sustainability is achiev-

able for other technologies as well. A technology should be considered "sustainable" if the intended or unintended consequences of its use do not force an abandonment of this technology.

Resource size limits any technology's sustainability. Even renewable resources are not infinite. For practical purposes we consider a technology as "sustainable" if resource depletion is not an issue on a time scale for which humans can reasonably plan.

Coal consumption for the foreseeable future is not limited by resource availability. Worldwide consumption (including lignite) is on the order of 4 to 5 Gigatons (Gt) per year (United Nations, 1997). Accessible coal is estimated to exceed 10,000 Gt and currently recoverable proven reserves of coal are in the order of 1000 Gt (United Nations, 1997). With the current consumption rate, the proven coal reserves would last at least two centuries, and the entire coal resources would last 20 centuries. Coal's availability virtually guarantees that energy will not run out for many generations. The challenge to coal's sustainability lies in the environmental impact of consuming such a staggering volume of material. Small concentrations of impurities in the coal, multiplied by a large rate of consumption, amount to large emissions of problematic materials. Many of these environmental impacts have been addressed for some time. With regard to impurities and undesirable combustion byproducts, technology is already moving towards zero emission coal. The one serious challenge to sustainability of coal that so far has not received adequate attention is the emission of CO_2.

4 THE CARBON DIOXIDE PROBLEM

The safe and permanent disposal of carbon dioxide is the most difficult challenge to the sustainability of coal. The industry shares this problem with all other fossil energy sources. Coal is carbon intensive, it generates more CO_2 per unit of energy than most other energy resources. There are however, natural gas wells with such high CO_2 content that the raw gas is even more carbon intensive than coal. For example, the Natuna field, which is the largest natural gas field in the world, contains 71% CO_2. The largest carbon disposal operation, at Sleipner field off the shore of Norway, sequesters CO_2 from a natural gas well (Herzog et al., 2000).

In order for carbon not to accumulate in the atmosphere, or for that matter elsewhere in the carbon surface pool, future energy technologies need to provide the means of capturing the oxidized carbon and dispose of it in a safe and permanent manner. We emphasize the need for disposing of the oxidized carbon, i.e. CO_2, or carbonates, since all reduced form of carbon carry an amount of energy that is

comparable to the energy carried per unit of carbon by fossil fuels.

To set the scale for the problem, consider the fact that a century of CO_2 emissions at the current rate amounts to 600 Gt. This is more than the natural carbon content of the atmosphere. It matches the entire living biomass on the surface of the earth and it is 40% of the carbon found in soil and detritus. At 39,000 Gt of carbon, the ocean is the biggest reservoir of mobile carbon, mainly in the form of bicarbonate ions. However, using mobile carbon in the ocean as a yardstick is misleading because a change of about 1,000 Gt is sufficient to decrease the ocean pH everywhere by 0.3. Such a change in acidity would have substantial environmental effects. If we follow the trend set during the last century, the potential output during the 21st century could be 4 to 6 times larger than the initial rate of output at the beginning of the century suggests. If energy production stays on its current path, likely problems in the future are not limited to climate. Excess CO_2 in the atmosphere results in physiological changes in plants and animals and more subtle changes in ecological systems. The concomitant acidification of the ocean will pose its own problems to an ecological system, which seems to be quite sensitive to the pH of the water. Corals in particular are sensitive to such changes (Kleypas, 1999). A continuous rise in atmospheric CO_2 levels is not sustainable and steps must be taken to stop a further rise. While the debate of what level of CO_2 is tolerable is still ongoing, hardly anyone would advocate levels that exceed twice the preindustrial value. At this point the surface ocean pH would have changed by 0.3. Current worldwide increases in emissions suggest that this point is not far away and is likely to be reached by the middle of this century.

In order to stop the increase of atmospheric CO_2 one has to drastically reduce CO_2 emissions. At present, the oceans absorb CO_2 because the continuous rise in atmospheric levels maintains a gradient. As the increase is arrested, the gradient is no longer maintained and fluxes out of the atmospheric reservoir are greatly reduced. Model calculations suggest that even after doubling the CO_2 from preindustrial levels the steady state emissions must be exceedingly small. To maintain a constant CO_2 level, emissions must be reduced. Even at twice the preindustrial level of CO_2, sustainable emissions could rapidly fall to 30% of 1990 emission rates.

The consequence of these physical constraints is that as atmospheric CO_2 approaches the maximum tolerable level, the annual worldwide emission allowance will rapidly shrink. Dividing the world emission allowance evenly among 10 billion people would lead to a per capita allowance which is only about 3% of the current US per capita emission rate.

5 TECHNOLOGY FOR SUSTAINABLE COAL

To avoid the built-up of carbon in the surface pool, carbon needs to be shepherded through the entire energy cycle. In the case of coal, the carbon comes out of the ground, essentially as $CH_{0.8}$. The mixture also contains ash and impurities like sulfur, nitrogen, and heavy metals. A well-designed plant will combine the collection of CO_2 with the cleanup of all other pollutants. CO_2 generation is unavoidable; in order to extract the energy, either as electricity or as a chemical energy carrier free of carbon, the carbon needs to be oxidized. Carbon is either combusted with the oxygen from air or it is used to reduce the oxide of some other element, which then carries the energy in a carbon free form. Combustion with air complicates the CO_2 recovery because it carries a large amount of nitrogen through the combustion process. Not only does this greatly increase the potential for undesirable nitrogen compounds, it also dilutes the CO_2 by roughly a factor of four. To complicate matters further, CO_2 and N_2 are both gases suggesting a difficult separation problem. One approach to the problem is to separate the oxygen from the air and perform the combustion in either pure oxygen or a mixture of flue gas CO_2 and O_2. In either case the resulting combustion products will be dominated by CO_2 and water, which are easily separated.

The other option is not to bring in air at all, but shifting the oxygen from another compound to the carbon. A potential candidate here is water, which is reduced to hydrogen. One problem with this approach is that the stoichiometry and energy balance typically do not match and additional oxygen is needed to complete the transition while balancing the energy of the reaction. For example, in transferring the oxygen in water to carbon and forming CO_2 an additional amount of energy, about 40% of the heat of combustion of carbon, is needed to complete the reaction.

After CO_2 has formed, it needs to be separated out in a concentrated stream that can be readily disposed of. At issue is the nature of the gas formed. The admixture of particulates, sulfur, nitrogen etc. can make for a corrosive mixture that rules out some of the more advanced ways of separation. For example, such an environment will challenge membrane technologies. Absorption of CO_2 during the reaction provides a most convenient approach. Carbon dioxide acceptor processes fall into this category.

6 ANAEROBIC HYDROGEN PRODUCTION FOR ZERO EMISSION COAL

With the exception of biomass sequestration, which takes CO_2 directly out of the air, sequestration will

require a concentrated input stream of CO_2. Thus, sustainable coal technology not only needs CO_2 disposal options but also CO_2 collection options. Retrofitting existing power plants for collection of CO_2 is possible but it is a costly proposition. A better approach for the long term is to reoptimize a power plant with the new design constraints in mind. New designs will look quite different, since the new optimum is not likely to near current designs.

One approach to zero emission coal is the CO_2 acceptor process, which has been pioneered by Consolidated Coal in the sixties and seventies. The basic idea is to assist the reforming shift reactions, which make hydrogen from water by turning carbon into CO_2 and which use CaO to remove the CO_2 from the reaction products. Not only does the reaction with lime remove one of the reactants and thus let the reaction proceed further, but it also provides in the exothermic carbonation reaction the energy that is required to complete the shift reaction. It is an accident of nature that the reaction

$$CaO + C + 2H_2O \rightarrow CaCO_3 + 2H_2 \qquad (1)$$

is balanced in enthalpy. Starting with liquid water the reaction is exothermic by a mere 0.6 kJ/mole. The heat of combustion of carbon which sets the scale is 393kJ/mole (Figure 1.).
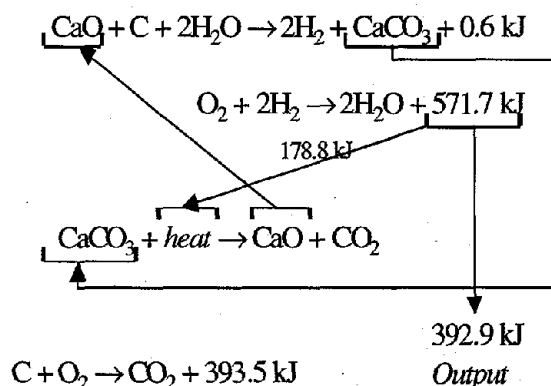

Figure1. Energy balance in hydrogen production from coal

Ziock and collaborators are developing an anaerobic process for hydrogen production from coal (Lackner et al., 1999b) in which coal, water and lime are used to form hydrogen and limestone as an intermediary. The hydrogen when it is combusted releases an amount of energy, which combines the heat of combustion of coal with the heat of carbonation of CaO. A fraction of this combustion heat can be used to calcine the CaO and thus extract the CO_2 from the process. The remaining energy in the hydrogen than matches the heat of combustion of the coal. If all the hydrogen is run through a high tem-

perature solid oxide fuel cell it generates an amount of electricity that nearly matches the heat of combustion of coal. The thermodynamically unavoidable waste heat is of a sufficient quality that it can be used to calcine the calcium carbonate. Thus the effective efficiency of the fuel cell is boosted by the ratio of the heat of combustion of hydrogen to the heat of combustion of carbon. In an indirect manner, this is a carbon-based fuel cell The theoretical efficiency of a carbon burning fuel cell would be 102% based on the ratio of Gibbs free energy to enthalpy. The process of making intermediate hydrogen is, however, not reversible and consequently the theoretical limit of this specific approach at 93% is somewhat lower. Practical implementations will fall short of this ambitious goal. Nevertheless this approach has the potential for extremely high efficiencies (Figure 2.).
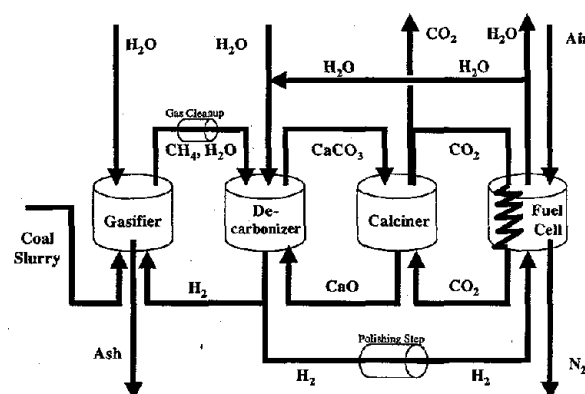
Figure 2. A block diagram of CaO driven hydrogen production system

The economics of this process look very promising. The process steps are not that different from pressurized fluidized bed technologies which are used in upgrading conventional coal fired plants for merchant plant installations. As a means of producing hydrogen this process may prove very cost efficient. Ultimately, of course, it relies on the price difference between coal and natural gas. It is worthwhile pointing out that nearly all attempts of utilizing coal have simpler counterparts for natural gas. Thus the future of coal will depend on the availability and price of natural gas. The advantage of coal is in its lower starting cost.

7 SEQUESTRATION TECHNOLOGIES

Sequestration in its broadest sense is any technology that keeps CO_2 out of the atmosphere. Thus, sequestration technologies can prevent the accumulation of CO_2 in the air without curtailing the use of fossil fuels. Sequestration can be accomplished in

a variety of ways. CO_2 could be collected at the point of combustion or later taken from the air. CO_2 could be stored in gaseous form or could be chemically transformed before it is disposed as waste. It has been suggested that some of it is recycled back into the economy.

Currently, only biomass generation extracts CO_2 from air. The 1:3000 dilution has made this approach look too difficult. On the other hand the CO_2 in a volume of air represents an amount of heat of combustion that exceeds the kinetic or wind energy of the same amount of air by two orders of magnitude (Lackner et al. 1999a). Since wind energy appears close to economically viable, CO_2 extraction from air may prove to be attractive. Extraction from air would eliminate the need for a dedicated infrastructure for the transport of CO_2 and no change would be needed in present combustion technology. Extraction from air would be particularly useful in counteracting the emissions of small, distributed and often mobile sources of CO_2, which together amount to about half of all CO_2 emissions.

The other alternative would be to collect CO_2 at the site of combustion. While difficult for mobile sources, it is quite easy for large stationary sources. It is the obvious method of choice if the flue gas is sufficiently rich in CO_2. In this case, chemical scrubbing or membrane separation techniques can be used (Meisen & Shuai, 1997). Retrofitting existing power plants with low concentration of CO_2 around 10% to 15% in the flue gas make this a costly option raising the cost of electricity by 30% to 40%. Integrating CO_2 collection into an integrated gasifier combined cycle plant is much easier because pressures are higher and the exhaust is much richer in CO_2. In the above mentioned plant designed to produce hydrogen, collection of CO_2 comes naturally and is achieved with hardly any incremental cost. 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 (Lackner et al., 1998). Transporting and shipping CO_2 will not stop sequestration. Pipeline technology for transporting carbon dioxide is already in place and costs have been estimated at \$0.01/ton km (Audus et al., 1995). Recent studies for very large pipelines have arrived at even lower costs. However, the options for turning CO_2 into valuable products are extremely limited considering the fact that the volume of CO_2 is very large. CO_2 emissions in the US alone amount to about 20 t/year per person (EIA, 1998). This is more than three times per capita crushed stone consumption in the US. Considering the value of crushed stone today, transportation costs alone would make this option very unattractive.

We can easily rule out carbon recycling in the form of plastics (Halman, 1993, Arresta, & Tommasi, 1997) or other organic compounds. The synthesis of nearly all carbon rich products which re-

quire substantial amounts of energy are usually far in excess of what has been extracted at the power plant.

7.1 Biomass Sequestration

Biomass generation has been considered as a method of sequestration. Photosynthesis is a natural process and extracts CO_2 from air to form starch or similar organic materials by adding H_2O and sunlight. Biomass can accumulate in standing forests or other green areas. This however is a means of collecting energy, which ultimately will be wasted. It is difficult to store the perpetual accumulation of carbon as biomass. A mature forest will lose about as much biomass as it generates. Furthermore, because collection rates are very small (Ranney & Cushman, 1992), one needs to dedicate unrealistic amounts of land or ocean to use this option as the sole means of sequestration of CO_2 (Lackner et al. 1998, Sedjo & Solomon, 1989). The annual collection of carbon on an acre of land at best compensates for a couple of minutes worth of CO_2 from a one GW power plant (Ranney & Cushman 1992). Natural forests would fall far short of this number.

7.2 Underground Injection

Instead of releasing it to the air, CO_2 can be injected into suitable geological formations for permanent storage. This idea is already practiced at a limited extent for various purposes. For example, because of high carbon tax in Norway (\$55/t of CO_2) CO_2 stripped from natural gas is injected into an aquifer 1000 m under the sea floor in the North Sea (Kaarstad & Audus, 1997). It is also a common practice in crude oil and natural gas production to inject CO_2 to increase production rates. In another case, CO_2 is injected to recover methane from deep coal seams (Gunter et al., 1997). Since CO_2 is adsorbed much more strongly than methane, CO_2 exchanges places with the adsorbed methane, which can then be produced and CO_2 remains behind fixed in place.

7.3 Ocean disposal

Ocean disposal has been extensively studied (Herzog et al., 1997). There are various forms, which differ in how and where CO_2 is introduced into the ocean. CO_2 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. CO_2 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 CO_2 becomes denser than water and forms a lake on the

bottom of the ocean, which only gradually dissolves into the surrounding water (Herzog et al., 2000).

Ocean circulation guarantees that over time the highly soluble CO_2 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. Approximately 1000 Gt of carbon added as bicarbonate ions to the ocean would change the overall pH by 0.3. 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.
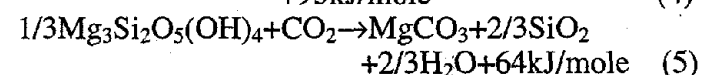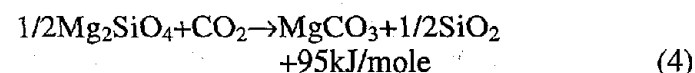
7.4 Carbonate Disposal

Except biomass generation, all sequestration methods consider disposing CO_2 in gas form. A newly emerging technology suggests that it is not only feasible but also quite advantageous to dispose of CO_2 in the form of carbonates (Lackner, et al. 1998). This idea was first suggested by Sefritz (Seifritz, 1990). The reaction of CO_2 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 CO_2 as a solid mineral carbonate (Lackner et al., 1995, Lackner et al., 1997a). The resulting waste product is environmentally safe and thermodynamically stable. There is no shortage of raw materials to bind with CO_2. In fact, the known resources for such raw materials are more than what is needed for even the most optimistic estimates of fossil energy reserves (Lackner et al., 1997a). The reaction is well known to geologists because it occurs spontaneously on geological time scales.

The carbonation reaction can be shown by the simple reaction of binary oxides, MgO and CaO. These reactions are exothermic.

$$CaO + CO_2 \rightarrow CaCO_3 + 179 \text{ kJ/mole} \qquad (2)$$

$$MgO + CO_2 \rightarrow MgCO_3 + 118 \text{ kJ/mole} \qquad (3)$$
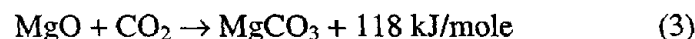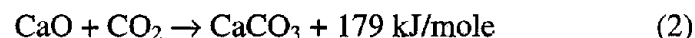
Even compared to the heat released in the combustion of carbon (394 kJ/mole), these reactions release substantial heat. In nature, however, calcium and magnesium are rarely available as binary oxides. They are found typically as calcium and magnesium silicates. The carbonation reaction is still exothermic for common calcium and magnesium bearing minerals. In such cases however, the heat release is reduced. As an example consider the carbonation reactions of forsterite and serpentine. For forsterite and serpentine respectively:

$$1/2Mg_2SiO_4 + CO_2 \rightarrow MgCO_3 + 1/2SiO_2$$
$$+ 95 \text{kJ/mole} \qquad (4)$$
$$1/3Mg_3Si_2O_5(OH)_4 + CO_2 \rightarrow MgCO_3 + 2/3SiO_2$$
$$+ 2/3H_2O + 64 \text{kJ/mole} \qquad (5)$$

Both of these reactions are favored at low temperatures. In nature magnesite and silica are common in serpentinized ultramafic rocks. Their formation is due to natural CO_2 –rich fluids percolating through mineral deposits. Magnesite is stable and not likely to release the bound CO_2 again.

One can accelerate the process by injecting concentrated CO_2 into underground formations which are likely to react with it. These include limestone reservoirs that would form bicarbonates, or silicate rocks that can form carbonates. The advantage of forming carbonates in underground injection is that it solves the problem of long-term stability. Once carbonates have been formed the CO_2 can no longer escape to the surface. The concern about seepage is heightened by the large volumes of CO_2 that need to be injected underground. At a nominal density of water a one Gigawatt coal fired power plant of 33% conversion efficiency would generate a volume of CO_2 that would have to raise the ground over a 10km by 10km area by 7 cm.

An alternative route to forming stable mineral carbonates is an above ground industrial process. In this case the rock is mined, ground up and reacted with CO_2 to form solid mineral carbonates. The advantage of the above ground process is that the resulting material is much better controlled. Rather than relying on circumstantial evidence that the carbonate indeed has been formed or will form in the foreseeable future one has a product in hand and can determine its quality.

Lackner et al. (Lackner et al., 1997b) have been studying this reaction over the last few years with the purpose of developing an economically viable above ground process that accelerates the natural reaction rate so that it can be performed cost-effectively. Since the reaction generates heat, the aim is for an implementation without an external supply of energy. At present, this process is still in an early research phase. The goal is to achieve a cost of about $20/t of CO_2 but this still needs to be demonstrated. The long-term stability of the waste product makes the process appealing.

Figure 3. shows a 2 GW power plant fed from a 9 kt/day coal mine by pipeline at a serpentine mine by pipeline at a rate of rate of 18 - 20 kt/day coal slurry. The plant produces 2.6 kt/day of hydrogen, which is then combusted in a fuel cell. CO_2 emissions are captured and compressed and sent to a carbonation plant where the carbonation process takes place. Calcium and magnesium carbonates are solid which is desirable in above ground disposal. The materials formed can be stored at the serpentine mine as landfill and will not leave the disposal site. Magnesium proved more attractive since there are large deposits of magnesium rich minerals. Peridotite, and serpentinized peridotite rocks can have an MgO content between 35% and 40% by weight, whereas abundant calcium silicates rarely have more than 12 % to 15%
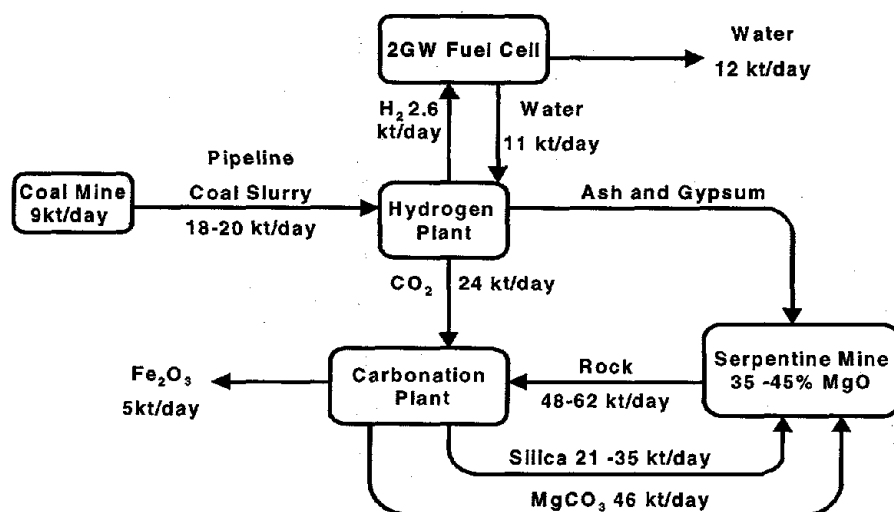
Figure 3. A block diagram of zero emission system

of CaO by weight. In addition, the magnesium silicates are more reactive and are therefore more suitable for above ground carbonation.

The process implies a large mining effort, but the areal extent of the mine is small compared to the coal mine that produces an equivalent amount of coal. Overburden on serpentinite rock is generally insignificantly small and the minerals occur in thick layers rather than thin seams. Nevertheless, the mass of material required is larger by a factor of six than the mass of coal that is used as fuel As a result, the formation of carbonate will have to be performed at the mine site, and the resulting silica and carbonates will be stored in the mine. Since volumes increase in the process, some modification of the local terrain's profile is unavoidable.

Mining costs appear to be quite low. The mining is similar to copper mining and the amount of peridotite required for a GW power plant is small compared to the amount of ore mined in a large copper mine. Cost estimates, based on other mining operations suggest a cost of about $8 per ton of CO_2.

Future research efforts will have to focus on the details of the chemical processing. Direct carbonation of the mineral rock is feasible but at this point still too slow to be economic. An aqueous process using hydrochloric acid that is completely recovered within the process has been demonstrated to be fast. However, the number of steps is too large and the large amount of steam generation makes the process energy inefficient even though the overall reaction is exothermic (Lackner et al. 1997a, Goff & Lackner 1998). A very similar process was suggested in the

past (Houston, 1945, Barnes et al., 1950) to overcome Mg shortages. A variation of this process which uses molten $MgCl_2$ salts to dissolve the rock is similar to a process Noranda will use in a commercial plant that utilizes serpentine mine tailings to produce metallic magnesium. The molten salt process for forming carbonates is currently under investigation. While the thermodynamics has been demonstrated, experiments verifying the kinetics are still underway. In summary the feasibility of carbonate formation has been demonstrated, but a more streamlined implementation will be required to be cost effective. However, reasonable assumptions about thermodynamically efficient processes suggest costs for the entire disposal process, including rock mining, crushing and milling, of about $20/t of CO_2. For a 66% efficient power plant this would add less that 1 cent to the cost of a kilowatt hour.

8 CONCLUSIONS

It is clear that the CO_2 problem needs to be addressed in a rational and systematic way. It is also clear that energy saving strategies, forestation and alternative fuels alone will not solve the problem simply because of huge quantities of CO_2 production. In the foreseeable future, however, technologies are expected to be on line for zero emission processes which will make coal, the most abundant fuel, become a sustainable resource for at least 2 centuries. These technologies will also help solve the

CO_2 problem associated with other fossil fuels by capturing CO_2 at the source of its generation.

Economically, coal has a strong advantage in that the raw resource is much cheaper. Coal cost at the minemouth is about $0.50 to $1.00 per GJ. The cost for natural gas is $2 to $3 per GJ by comparison. The low cost of coal is in part offset by larger handling cost and larger cleanup cost. When it comes to carbon sequestration, the lower cost of coal allows one to budget a certain amount for CO_2 disposal without losing the competitive edge. For example the price difference between nuclear and coal suggest a buffer of about $40 to $60 per ton of CO_2 (Herzog et al., 1997). Relative to renewable options like solar energy the margin is even higher. Another comparison is relative to natural gas. For every dollar difference in price between natural gas and coal, the cost of CO_2 capture and disposal can go up by $22/ton of CO_2. This scenario assumes that the price difference between coal and gas is reduced because coal needs to pay an additional cost for removing that amount of CO_2 by which it exceeds the output from natural gas power plants. For the sake of this discussion we assume comparable efficiencies and no additional CO_2 in the natural gas.

Processing of coal to produce hydrogen even without sequestering of CO_2 will pay in the short run to eliminate the problems associated with sulfur and nitrogen oxides emissions. It is conceivable that while for efficient and economic technologies are being developed for CO_2 sequestration a transition to hydrogen production can be implemented as a first step to zero emissions energy production systems.

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To: Klaus Lackner <ksl@lanl.gov>
cc:
Subject: paper

Dear Klaus,
I am pleased to learn that you are doing better. I am forwarding the
latest announcement from SWEMP, the symposium, announcing the
availability of the program.

The name of the symposium is :

Sixt International Symposium on Environmental Issues and Waste
Management in Energy and Mineral Production

It will be held at Calgary, Alberta, canada on May 30 - June 2, 2000.

I perhaps mentioned to you earlier. I organized the first one in 1990 at
Columbia. Since then this became a tradition. The symposia are held
every other year.

--
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Dear Colleague
Re: SWEMP 2000 May 30-June 2, 2000

The preliminary program for the Sixth International Symposium on
Environmental Issues and Waste Management in Energy and Mineral
Production to be held in Calgary is now available.

To obtain your copy please contact Ms Margaret-Anne Stroh, University of

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Dr. Raj Singhal
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