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Can Fossil Carbon Fuel the 21st Century?

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Abstract

Fossil fuels, despite their drawbacks, have been fueling the world economy for the last two centuries. They have proven abundant, easy to use, and low in cost. Contrary to common belief, fossil fuels are not likely to run out any time soon. For the foreseeable future, fossil fuels may continue to be the most cost-effective energy resource, even as concerns over climate change will force the implementation of technologies to capture and dispose of the carbon dioxide generated in their use. With a successful implementation of the carbon management technologies that are under development today, the use of fossil carbon could be sustained for at least another century.

Introduction

FOSSIL CARBON IS an energy source with many flaws. Since fossil fuels are derived from a non-renewable, finite resource, their use cannot be sustained indefinitely. The concentration of oil and gas in a few regions of the world has become the source of international tensions. Pollution, ranging from emissions of SO_x and NO_x to fine particulates and mercury, plague electricity generation, the transportation sector, and other uses of fossil fuels. Power generation from fossil fuel generates carbon dioxide, which is a potent greenhouse gas. Its continued emission to the atmosphere raises serious concerns over climate change. Furthermore, carbon dioxide is an acid, and it is important to plant and animal physiology. Consequently, the environmental impact of increased fossil fuel consumption is not limited to climate change concerns. As world energy consumption increases, the consequences of the inherent flaws of fossil fuels become amplified and require more extensive corrective measures. If not solved, these problems will start to severely limit the role of fossil fuels.

Despite all the obvious drawbacks, fossil energy has proven itself to be the most cost-effective, and most easy to use energy resource. It has propelled modern societies to historically unprecedented wealth. Today, fossil energy provides 85% of all commercial energy. None of the currently available alternatives could replace fossil energy in the foreseeable future without drastic increases in cost, and—in some cases—one might expect environmental impacts on a similar scale to those of fossil fuels. It is important to realize that issues that hardly matter at the Megawatt scale, and are barely noticeable at the Gigawatt scale, can turn into major obstacles, if power production increases by yet another three orders of magnitude.

The accumulation of carbon dioxide in the atmosphere, which is the cause of climate change, presents the most difficult challenge to the continued use of fossil energy. Stabilizing the carbon dioxide concentration in the atmosphere at any reasonable level will require drastic reductions in carbon dioxide emissions. For fossil energy to play a role in a carbon-constrained world, the carbon dioxide resulting from the use of fossil fuels will have to be captured and disposed of safely and permanently. This will require substantial changes in the way fossil fuels are used. Nevertheless, for the foreseeable future, it may be easier to render fossil fuels environmentally acceptable than to replace them.

Sustainable Development

Modern societies have a large ecological footprint. Virtually the entire world ecosystem is affected by human activities (Vitousek et al., 1997). Continued economic growth in the developed nations, as well as any effort of achieving a decent standard of living in the developing nations, will amplify this trend and cause severe global ecological change. In order to reverse the trend without abandoning economic growth, science and engineering will need to greatly reduce the environmental impact of modern technologies. Sustainable development is an attempt to achieve this goal.

Sustainable development will fail, unless there are sufficient supplies of affordable energy. The transformation that gave the developed nations their historically unprecedented wealth, comfort, and security has been founded on plentiful and affordable energy. Four-fifths of the world population still have to go through this transformation. Roughly two billion people are still without electricity. Supporting this transformation and the improved standard of living of a future world population of 10 billion people will require far more energy than is consumed today. Energy consumption and gross national product are tightly linked (Hoffert et al., 2002), making it virtually impossible to support rapid economic growth without corresponding increases in worldwide energy consumption. If 10 billion people were to consume energy like the United States does today, world energy consumption would grow by a factor of 10.

Unfortunately, none of the current energy technologies would be able to support even a fraction of this growth (Hoffert et al., 2002). Some energy technologies, such as photovoltaic solar power, are still far too expensive to support large-scale economic growth. Energy technologies like conventional fossil fuel–based technologies are too harmful to the environment to operate on the necessary scale, while others, like hydroelectricity, lack the resource base or the scope necessary to operate at the necessary scale of tens of Terawatts. In short, major technological advances are required to provide the energy basis necessary for sustainable global development.

By failing to address this technological need, the developed nations would allow energy to become scarce despite a large resource base. The resulting shortages would pit developed nations, who still demand continued economic growth, against developing nations, who desperately need economic growth. In a competition for energy, the economic muscle of the developed nations would likely stifle economic growth in the developing nations, and thus create political strife and international instability. To avert a crisis, science and engineering must pursue every technological avenue that holds a reasonable promise of clean, cheap, and copious energy for 10 billion people aspiring to a Western standard of living. Among these technological options are solar energy and wind energy, and fission and fusion energy. However, given the prevalence of fossil energy and its inherently low resource cost, one also must pursue any technological change that could render fossil fuels environmentally acceptable.

Could Fossil Fuels Ever Be Sustainable?

To many observers, sustainable development based on non-renewable energy sources seems a contradiction in terms. To these observers “sustainable” and “renewable” are virtually synonymous. It would, however, be a pity if sustainable development were to be sacrificed to such semantic rigidity. No technology can be sustained indefinitely; even the sun’s energy supply will be depleted some time in the distant future. To avoid this trap, we have proposed the following definition, which acknowledges that no technology or process can be sustained indefinitely (Yegulalp et al., 2001):

> A technology or process is sustainable at a specific scale and for a specific time, if no intended or unintended consequences will force their premature abandonment.

Clearly, resource depletion within the intended time frame would render a technology unsustainable. Limiting the time frame may seem to weaken the meaning of sustainable, but on the other hand the term has been strengthened considerably by explicitly including other reasons for abandonment. For example, processes can be unsustainable at a certain scale due to their environmental impact even though they are not at all affected by resource limitations.

Quite likely, fossil energy technologies will remain in the latter category for which limitations other than resource availability dominate. The fossil carbon resource base is very large, in excess of 5000 Gt of carbon (GtC) (Rogner, 1997). This should be compared to an annual world fossil fuel consumption of 6GtC (EIA, 2002b). Based on past experience, it is likely that the economically accessible resource base grows as technology advances. Undersea methane hydrates alone could boost the resource base by an order of magnitude (Kvenvolden, 1993).

Limitations in one category of fossil fuels or another are of minor consequence, because even with today’s technology the various fossil fuels are readily interchangeable (Lackner, 2002). Whereas the track record suggests that it is difficult to predict how long oil and gas reserves will last (Economist, 1997), if they were to fall short, other fossil fuels could easily fill in the gap. Tar sands can compete with natural crude oil (Yui and Chung, 2001), and SASOL, a South African Company, has demonstrated practical implementations of coal liquefaction (Dry, 1987). Economies of scale and the learning involved in scaling up from a few plants to a worldwide production system could easily reduce the cost of liquefaction by a factor of two. If future oil and gas shortages were to drive a large-scale introduction of coal liquefaction, these cost reductions would keep the long-term cost of energy at or below that of today's crude oil–based energy prices. Other technologies may prove superior, but since coal dominates the fossil fuel reserves, the existence of such conversion technologies already assures that fossil energy resources could last for centuries, even under scenarios of greatly increased consumption. The limitations to fossil energy use, which increased R&D could help overcome, arise from greenhouse gas emissions and other environmental impacts not resource shortfalls.

Carbon dioxide emissions to the atmosphere represent the most immediate and most difficult constraint on the use of fossil energy. For fossil fuels to retain a substantial role in the future energy mix, carbon management technologies to capture and sequester carbon dioxide safely and permanently need to be introduced on a global scale. With carbon management, fossil fuels could sustain economic development for several centuries and allow operation at a scale that could dwarf current energy consumption. At even longer time scales, additional environmental impacts, or eventually perhaps resource limitations, would render a fossil fuel economy unsustainable. Under the umbrella of a century of energy assurance, alternative energy technologies could be developed to the level of maturity at which they would be ready to take over. Long before fossil energy becomes unsustainable, alternatives may have acquired a competitive edge that would drive the transition to a different energy base. Eventually, this transition will have to happen, justifying R&D efforts into developing promising new energy technologies, even if carbon management technologies were already proven. However, present limitations in alternative energy options suggest that the promise of low-cost sequestration technologies may make it the best alternative for assuring access to energy for the next few generations.

The Scope of Carbon Reductions

The concern over climate change by itself suggests that carbon dioxide emissions to the atmosphere will have to be curtailed drastically. Predictions about the expected climatic impact vary, not only because of uncertainties in the expected emission profile, but also because modeling of the climate is difficult and fraught with uncertainties. It is, however, undisputed that carbon dioxide is a potent greenhouse gas and as such will have a noticeable effect on climate. Changes over the last century are roughly in line with what would be expected from a fossil fuel–driven greenhouse effect, but it is virtually impossible to rule out other agents of change being at least in part responsible for the observed change. Climate change brings with it a raft of other changes. Some, like more amenable conditions for agriculture at high latitudes, are seemingly improvements over the current climate; others such as ocean rise, or a substantial desertification expected in many regions of the world, would require substantial adaptations by humans and other species (Hall and Manabe, 2000).

This is not the place to discuss in detail the effects of climate change. It is, however, important to point out that carbon dioxide does not only have an impact on the radiation balance of the planet, it also directly affects the environment. Carbon dioxide is physiologically active; among other things it directly affects the efficiency of photosynthesis. It is involved in maintaining a constant blood pH; and it also plays an important part in controlling mammalian respiratory activity. As a consequence, one can expect direct ecological impact of an increased atmospheric concentration of carbon dioxide even in the absence of climate change. Rather than considering increased levels of carbon dioxide in the atmosphere as fertilizing plant growth, one might want to consider the effect to be more akin to eutrophication with all its unintended side effects on a complex ecological system that is built around a certain balance among its various components.

Carbon dioxide is also a weak acid that affects, for example, the chemistry of oceanic surface water. The surface ocean and the atmosphere are approximately in chemical equilibrium: a doubling of carbon dioxide in the atmosphere roughly doubles the $[H^+]$ concentration in the water, and reduces the carbonate ion concentration $[CO_3^{-2}]$ by a factor of two (Butler, 1991). Such changes have direct impacts on ocean biota that are independent of those caused by rising surface water temperatures. Specifically, doubling the carbonate ion concentration in the surface ocean is known to reduce the growth rate of coral reefs by more than 30%, raising serious concerns (Langdon et al., 2000; Kleypas et al., 2001) over their continued viability under a doubling of the preindustrial carbon dioxide concentrations.

Because carbon dioxide plays an important role in a variety of biogeochemical processes, drastically changing its concentration in the atmosphere must be considered carefully. While reasonable people can debate the maximum allowable atmospheric concentration of carbon dioxide, at some level stabilization will be necessary. From a practical point of view, it would take great and immediate efforts to stabilize carbon dioxide levels before they have doubled from the preindustrial value of 280 ppm. Under business-as-usual scenarios, carbon dioxide concentrations could triple or even quadruple by the end of the 21st century. While one cannot be absolutely certain that such a change would be too harmful for simple adaptation strategies, one cannot rule out detrimental or even catastrophic changes, either. There is undoubtedly a substantial potential for harm in a system that is known to be unstable (Broecker, 1997), and whose limits of stability are ill understood. The changes wrought and their consequences will be completely outside of any human experience.

As noted above, the problems caused by injecting excess carbon into the environment through fossil fuel use transcend the climate-change concerns brought about by raising the concentration of carbon dioxide in the atmosphere. A more useful concept may derive from considering the total excess carbon that can be injected into the environmentally active carbon pools. These pools encompass the atmosphere, most—if not all—of the oceans, the biologically active carbon in living organisms, and the organic carbon stored in the soil. Taken together these reservoirs of carbon have only minimal exchanges with even larger and environmentally inert carbon reservoirs like mineral carbonates in the earth crust or deeply buried fossil carbon. Carbon once entered in the environmentally active pool will stay there for millennia.

Carbon emissions over the next century are likely to be large compared to the natural uptake capacity of the active carbon pools. This stands in marked contrast to the carbon dioxide emissions that have been generated so far. At approximately 300 GtC, they are undoubtedly large, but distributed between atmosphere, ocean, and terrestrial biomass, their total is still small compared to natural uptake capacities. At the present rate of emission, the next 300 Gt of carbon will take less than 50 years. A carbon consumption of 2000 GtC over the course of the 21st century is well within the current trajectory of growth. It would require slightly more than an average of three times current consumption. At such a level of consumption, excess carbon would dominate the natural uptake capacity of the planet.

The actual level at which carbon dioxide in the atmosphere will have to be stabilized will greatly affect the time frame over which action will have to be taken. On the other hand, since to a good approximation it is the integral that matters, the severity of the reductions is ultimately the same. Stabilizing carbon dioxide in the atmosphere will require drastic reductions; eventually global emissions must be reduced to close to zero. On a time scale of decades to a century, stabilization requires a reduction of worldwide carbon dioxide emissions to less than 30% of what they are today (Schimel et al., 1995). The lifetime of carbon in the environment is so large that limiting total excess carbon is tantamount to limiting total integrated fossil fuel consumption quite likely to a number that is substantially smaller than the available carbon resources. The fossil carbon resources in excess of this limit represent a large, untapped, low-cost energy resource. Even if the people of today's generation would agree to leave this energy in the ground, it would remain forever a tempting target for exploitation. The only long-term assurance that it will not become the cause of severe global environmental degradation is to provide cost-effective technological means of eliminating the environmental consequences of its use.

Reducing total carbon emissions will greatly limit the per capita emission budget. A population of 10 billion people with an annual carbon budget of 2 Gt (30% of the present budget) would have an average per capita emission that amounts to only 3% of the actual current per capita of emissions in Canada or the United States. However, there is a transition time in which conventional fossil energy may still play an important role, but carbon-neutral energy will have to be phased in to fill the gap between fossil energy with still acceptable emissions and the energy that would be required to maintain healthy worldwide economic growth. In order to stabilize near 550 ppm of carbon dioxide in the atmosphere, which is twice the preindustrial level, carbon-neutral energy must be developed immediately. The amount of carbon-neutral primary power required by the year 2050 has been estimated to be 15 TW (Hoffert et al., 2002). This is more than all of today's fossil energy consumption. While this may seem large, consider that energy consumption over the last 50 years grew by a factor of 4 to 5 (Schock, 1992; EIA, 2002a). Under similar growth conditions, 15 TW of carbon-neutral energy would only provide 30% of total power generation. In the first half of the 21st century, emissions from conventional fossil fuel consumption would still be growing dramatically.

If fossil fuels combined with carbon capture and carbon sequestration were to provide the bulk of carbon-neutral energy, one would have to aim at sequestration rates on the order of 9 GtC/yr by 2050, and by the end of the century at rates that could be several times larger. Over the course of the century, total carbon sequestration would most likely exceed 1000 GtC. On an even longer time scale, fossil fuel reserves point to a possible total carbon sequestration of 5,000 GtC or more.

Inasmuch as re-emission to the atmosphere must not by itself raise greenhouse gas concerns, leakage rates from sequestered carbon storage must remain below a certain threshold. The maximum tolerable leakage rate still needs to be established, but it is most likely substantially below the 2 Gt/yr annual emissions, which in the IPCC model calculations seem to define the medium-term emission limit of stabilized carbon dioxide levels. If leakage rates were too high, future generations would be faced with climate change not of their own making.

Leakage rates, R, and storage times, τ, are connected. Short storage times combined with large storage volumes, Q, imply large leakage rates; the approximate relationship is given by $R \sim Q/\tau$. Initially, the stored quantities of carbon are small and storage time requirements are minimal. However, as stored quantities increase, an annual leakage limit that gives future generations some carbon dioxide emission allowance and thus has to stay substantially below 2 Gt/yr would soon start to drive up minimum storage time requirements. For the full fossil carbon stock, the lifetimes will have to be many thousand years, possibly exceeding tens of thousands of years. Optimal strategies for phasing in leakage constraints depend on one's expectation for future use of fossil fuels, and on one's understanding of the rates at which excess carbon is gradually removed from the environment by natural mechanisms. If carbon storage of the 21st century were to exceed 1000 GtC, carbon storage times virtually from the beginning would have to be measured in centuries.

Carbon Sequestration

Over the last decades, many methods have been suggested for carbon sequestration, beginning with Marchetti's idea of injecting carbon dioxide into the outflow of the Strait of Gibraltar, which would deposit the carbon dioxide in the deep Atlantic (Marchetti, 1977). From there, a variety of ocean storage methods have been devised (Herzog and Drake, 1996). Another class of storage schemes involves biomass and soil carbon uptake. Ocean fertilization methods combine the two ideas.

The large capacity demands and accompanying storage time constraints render these and many other sequestration methods irrelevant or marginal for the carbon budget of the 21st century. The world's entire biomass is only 600 Gt. Even a 20% change in that amount would require major efforts in land (or ocean) management, but at the current rate of emission it would take only 20 years to fill up this capacity. Left unattended, most of this carbon would be released in matter of decades. Since deforestation did not play a major role in carbon dioxide increases, it stands to reason that reforestation cannot appreciably reduce carbon dioxide concentrations either.

Ocean turnover times are around 800 to 1000 years, making even these storage times look short compared to what is required for the extended use of fossil carbon. In addition, the amount of carbonic acid that can be added to the ocean is limited. The relevant comparison is not to the dissolved inorganic carbon in the ocean (39,000 GtC), but to the far smaller amount of carbon in carbonate ions in the ocean. This number is around 3500 GtC. For every mole of carbonic acid added to the ocean, charge neutrality demands that one mole of carbonate ions is replaced with two moles of bicarbonates. Therefore, dissolution of carbon dioxide drives down the carbonate ion concentration, greatly changing the chemistry of ocean water. Carbon consumption of the 21st century could easily exceed the maximum uptake capacity of the entire ocean.

In any case, moving excess carbon from one environmentally active carbon pool to another is not a recommendable strategy. Instead, it is likely to trade one environmental problem for another.

Technically feasible at a large scale is the underground injection of carbon dioxide into permanent storage reservoirs. Underground injection is a method that could be used virtually immediately. It is practiced in tertiary oil recovery in West Texas.

These oil fields consume approximately 20 million tons of carbon dioxide annually (Ruether et al., 2002). The carbon dioxide, which is extracted from natural underground carbon dioxide wells in southern Colorado, is pipelined to West Texas and fetches a price between $10 and $20 per ton of carbon dioxide. A large number of oil reservoirs could benefit from the injection of carbon dioxide, but most of them are not in close proximity to convenient carbon dioxide sources. By using the carbon dioxide to extract additional resources from the ground, the cost of phasing in sequestration could be greatly reduced. However, oil wells and gas wells are clearly insufficient to store all the carbon dioxide. Estimates of oil field capacities are on the order of 30 GtC (Holloway, 2001) and coal bed methane reservoir sizes may even be smaller (Davison et al., 2001). In relatively short order, underground injection will have to move on to other, larger reservoirs that lack the economic benefits of recovering additional fuels.

There are large saline reservoirs that could accept far larger amounts of carbon dioxide than can be stored in oil and gas wells. The idea has already been tested in Statoil's Sleipner field in the North Sea, where several million tons of carbon dioxide have been injected underground. The ubiquity of saline reservoirs hints at a huge uptake capacity, far in excess of what would be required. However, safety concerns and leakage constraints could greatly reduce the practically available volume. At this stage, it is not clear how much carbon dioxide can be safely injected into such underground volumes. The total amount of carbon dioxide that needs to be injected is very large, and unlike in secondary or tertiary recovery, the pressure in the formation has not been relieved prior to injection, but it is rising above its normal value from the first day of the injection. As a consequence one must assure that increased pressures will not cause fissures to widen, which could lead to seismic instabilities and may open pathways for the carbon dioxide, which underground tends to be naturally buoyant. Thus carbon dioxide could escape from the intended reservoir and begin an uncontrolled journey toward the surface.

Proving to everyone's satisfaction that an underground reservoir is stable and will not leak for many thousands of years is not a trivial matter. In effect stability will have to be demonstrated for each individual field. Complications could arise from prior penetrations of the field, difficult seismic situations (Healy et al., 1968), and the uncertainty of how pressure and fluid flow might couple different underground reservoirs. There is a substantial experience with regard to these issues in the injection of hazardous waste into underground reservoirs (de Graaff, 1998). Nevertheless, over time, leakage constraints will become more severe, and the cost of reservoir characterization and testing of new reservoirs is likely to go up as demands on the quantity and quality of the reservoir are gradually increased. Volumes involved are large. To visualize the scale of the sequestration, consider that the mass flux contemplated here is about an order of magnitude larger than present-day oil extraction.

Carbon dioxide is the anhydride of carbonic acid. This suggests neutralizing carbonic acid as an alternative to underground injection of carbon dioxide (Lackner, 2002). With the appropriate base, carbonic acid can be transformed into neutral carbonates or bicarbonates that are environmentally harmless and thus could be stored in many different locations. Carbonic acid is stronger than silicic acid and thus drives silica out of silicates and turns them into carbonates or bicarbonates. Carbonic acid can also be neutralized with carbonates, which in the process are turned into water-soluble bicarbonates. These weathering reactions occur spontaneously in nature, albeit with extremely slow reaction kinetics (Berner et al., 1983). For sequestration, these reaction will have to be accelerated. Nevertheless, carbonate- and bicarbonate-forming reactions are exothermic and thermodynamically favored. Carbon dioxide is not the unavoidable end product of the oxidation of fossil fuels. Instead, at least in principle, it is possible to extract additional energy from a carbon atom by letting the carbon dioxide react with a base to form carbonates or bicarbonates. However, all current implementations of this idea consume at least as much energy in the multiple process steps designed to accelerate the reaction as is gained in the overall process.

Based on considerations of available resources and chemical reactivity, likely base ions for the neutralization of carbonic acid appear to be magnesium, calcium, sodium, and potassium. Mineral deposits involving silicates and carbonates of these metal ions far exceed even the most optimistic estimates of fossil carbon reserves. Even specific types of deposits, like serpentine and peridotite rocks, for which the carbonation reaction has been successfully demonstrated, exist in such large deposits that there need be no concern over resource depletion.

Carbonation reactions could proceed in the ocean, underground, or above ground in an industrial setting. In each case, alkalinity needs to be provided in some form to neutralize carbonic acid. Either the carbonic acid leaches alkaline minerals *in situ*, or alkaline minerals need to be extracted, typically in mining or leaching operations. In the oceans, the injection of alkalinity is likely to raise concerns about environmental issues. For example, impurities present in the alkaline minerals used to neutralize carbonic acid could be a major obstacle for injection of alkalinity in the ocean. On the other hand, such alkalinity is already needed, inasmuch as the dissolution of carbon dioxide from the air adds acidity to the water. Adding alkalinity to the surface ocean would greatly reduce the environmental impact of carbonic acid, and as a not unwelcome side effect, it would sequester additional carbon dioxide. The storage capacity of the ocean for neutral bicarbonate salts is far larger than it is for carbonic acid. The storage scale in that case needs to be compared to the amount of bicarbonate ions already stored in the ocean, and thus probably exceeds ten thousand Gigatons.

Similarly, injection of a pH-neutral carbonate or bicarbonate solution underground, or injection of carbonic acid into a reservoir that rapidly neutralizes the acid, would greatly reduce concerns over the stability of carbon sequestration. Finally, industrial processing above ground allows the formation of solid carbonates that can be stored on site. A major advantage of this approach is that it allows for the inspection of the disposal product. Industrial mineral sequestration also keeps the disposal product confined to a small area. In contrast, water-soluble products stored above ground will get diluted and spread over large areas. Eventually they will find their way to the ocean. The tradeoff to consider is relatively large environmental impacts in a small area as opposed to small and diffuse environmental impacts on a global scale. To the extent that alkalinity is obtained by mining operations, the concentrated impact is unavoidable, and may actually be reduced by mixing carbonates with tailings of the mining process.

As of today, neutralization in the environment has received minimal attention; geochemistry in underground reservoirs has been considered, but very little effort has been made to consciously design reservoirs in which neutralized carbonic acid is disposed. Above-ground processing has been pursued to some degree. It has been shown that mining operations are cost effective. Mining, grinding, and milling will add less than $10/ton of carbon dioxide to the disposal cost. To set the scale, $10 per ton of CO_2 is equivalent to 0.3 to 1¢/kWh,[1] or 8.5¢ per gallon of gasoline.

To cope with the output of individual large power plants and eventually with the majority of all carbon dioxide emissions, mining operations would be large but not outsized compared to present practice. Indeed, because of the removal of a large overburden, the mass of material moved in an above-ground coal mine is two or three times larger than the mass of material mined in a serpentine mine of matching size. For serpentine, in contrast to coal, it is possible to choose an ore body that reaches the surface and is hundreds of meters thick. In terms of area, a coal mine could be an order of magnitude larger, as coal seams tend to be far thinner than serpentine deposits.

The economic and technical challenges in above-ground mineral sequestration do not so much lie in the mining effort, which is well understood, but in the complications of accelerating the carbonation reaction to the point that they are economically attractive. It has been shown that serpentine minerals can be carbonated with reaction rates that are sufficiently fast. For example, nearly complete reactions in less than 30 minutes have been achieved (O'Connor et al., 2002). However, the cost of activating the serpentine material in order to raise the reaction rates is still too high. At present the best way to activate serpentine rock is to heat it to ~650°C and hold it at this temperature for about an hour. The energy penalty for this dehydroxylation step is unacceptably high. The fact that the carbonation reaction releases an even larger amount of heat at a lower temperature does not remedy the situation. The heat of carbonation is of too low a quality to be of practical use.

If better ways of activation can be found, the cost of the material-processing step could be significantly reduced. Certainly the capital cost of pressure vessels that could contain the reaction at 10 atmospheres for a time span of 30 minutes to an hour is small compared to a budget of $10–$15 per ton of carbon dioxide.

At a total cost of $15–$30 per ton of carbon dioxide, the cost of mineral sequestration would be com-

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[1] The range reflects different carbon contents of different fuels and different conversion efficiencies.

parable to the cost of carbon dioxide capture and carbon dioxide transport. Thus it would not unduly change the overall cost balance. Even though in the near future, injection underground is certain to be cheaper, the cost of assuring long-term integrity of the underground storage may in the end render mineral carbonation competitive. By developing mineral sequestration to the point of demonstrated feasibility, one can guarantee long-term availability of fossil energy, which should be an important policy consideration.

Decarbonizing Energy

Most sequestration methods require a concentrated stream of carbon dioxide. The best place to capture carbon dioxide is at a large central source. The most attractive sources are large power plants that generate carbon-free energy carriers like electricity and hydrogen.

Hydrogen and electricity are the ultimate energy carries that are carbon neutral and cause minimal pollution at the point of use. By transferring the energy contained in fossil fuels to these energy carriers, one in effect decarbonizes the retail energy market and moves the burden of carbon sequestration as far as possible upstream. Centralizing carbon dioxide capture eliminates a large carbon dioxide transportation infrastructure, and allows the economies of scales required for sequestration options based on underground injection or serpentine mining.

Hydrogen, just like electricity, needs to be produced with an energy input. The energy required in any practical implementation will exceed the amount of energy that can be recovered from the hydrogen, regardless of the specific conversion process. The cost of hydrogen will exceed the cost of the energy that was used in its production. Therefore, the relatively high cost of electricity will make the electrolytic production of hydrogen on large scales highly unlikely. Electricity at 3¢/kWh costs $8/GJ. If one allows for a realistic conversion efficiency of 70% in the electrolyzer, the electric energy input into one Gigajoule of hydrogen (high heating value) would exceed $11. If hydrogen storage requires additional energy, the cost would increase even further. With the price of a Gigajoule of natural gas between $2 and $3, and a Gigajoule of coal at the mine site firmly below $1, chemical processes involving partial oxidation, and watergas-shift reactions are economically far more interesting than electrolysis. At present, hydrogen is predominantly produced with natural gas, resulting in prices around $6/GJ of hydrogen. Niche markets that can rely on extremely cheap electricity may remain, but such niches cannot grow to encompass a large fraction of the total energy market. Energy sources that must first produce electricity, which is the highest quality of energy available, cannot compete in the production of hydrogen. Until there are major technological breakthroughs that could change the situation, these cost issues makes it very unlikely that nuclear energy, solar energy, or wind energy will be major contributors to the production of hydrogen. The lowest-cost source of hydrogen are hydrocarbons, which include fossil fuels, and at a smaller level, biomass. In short, one needs to clearly separate the concept of a hydrogen economy from the optimal choice of a primary energy resource. As long as electricity remains expensive, a future hydrogen economy is likely to be based on fossil fuels (Ogden, 1999), and thus does not even address the carbon issue.

Fossil carbon can therefore remain the source of energy that drives an economy with carbon-neutral energy carriers. It is based on a system of large plants the transform a crude and impure energy ore into a stream of clean energy, and waste products that include carbon dioxide as well as other impurities.

Carbon Dioxide Capture and Zero Emission

Capturing carbon dioxide in an electric power plant or hydrogen plant requires major changes to the overall material flow in the plant. Such changes are different from those required in sulfur capture and other pollutant issues addressed today in that they involve the bulk of the mass entering and leaving the plant. Consequently, one should not think of introducing carbon capture as a minor correction to the plant design, but one should consider it a major reorganization. Not surprisingly, retrofits have proved to be very expensive (Herzog and Drake, 1996). On the other hand, a number of fresh designs look highly promising (Holt et al., 2000). The simplest designs that would accomplish this goal are combustion plants that are fed oxygen rather than air. In order to keep the combustion temperatures from getting too high, the oxygen input is diluted with recycled exhaust gas. Oxygen blown gasifiers have also proven feasible. However, all of these designs suffer major efficiency losses in order to capture the carbon dioxide.

To regain efficiency or even reach levels of efficiency unheard of in coal plants of the past, more advanced designs are necessary that combine high-temperature solid oxide fuel cells with internal heat transfer. The first representative of this kind is a plant design developed at Los Alamos, which has become known as the design of the Zero Emission Coal Alliance (ZECA) and now ZECA Corporation (Lackner and Ziock, 2001; Yegulalp et al., 2001; Johnson and Ziock, 2002). The ZECA plant combines a number of clean coal technologies developed for the Department of Energy into a novel power plant design that combines hydrogasification (Anthony and Howard, 1976), the carbon dioxide acceptor process (Fink et al., 1974; Silaban et al., 1991), and high-temperature solid oxide fuel cells with advanced heat transport designs to obtain 70% high heating value (HHV) conversion efficiency. The plant would transform the energy available in coal into electricity, while collecting all carbon dioxide into a concentrated stream without emitting any coal-derived gases and their impurities into the atmosphere.

This latter feature opens the door to a new and revolutionary approach to pollution control. Once carbon dioxide has been removed from the exhaust for sequestration, the only other component of the flue gas stream that cannot be condensed or precipitated out is the nitrogen that enters the power plant with the input air. Power plant designs that avoid mixing air with coal gases, such as the ZECA plant, do in effect eliminate the flue stack. As a result, a paradigm shift becomes possible. Rather than trying to reduce pollutant levels in the exhaust stream to ever lower levels by improving scrubbing and gas processing technologies, this approach cuts the Gordian knot and simply eliminates the exhaust stream. This radical approach prevents the emission of virtually all of the pollutants to the atmosphere. Instead, sulfur compounds and nitrates, as well as heavy metals and fine particulates, will be collected into solid or liquid streams that are subject to further processing.

The ZECA plant is not the only plant design that can accomplish zero emissions to the air. Instead, there are simpler designs that without great development efforts could be implemented today. These are based on the above-mentioned concept of using pure oxygen rather than air in the power plant. Such plants would be developed around an oxygen separation unit that extracts oxygen from air. Producing oxygen from air will consume roughly 20 to 40% of the energy released in the oxidation process. The penalty depends on the efficiency of the oxygen plant. The amount of oxygen required per heat output is to a first approximation independent of the choice of fuel. The heat of combustion of all hydrocarbons, ranging from pure carbon to pure hydrogen, is roughly the same if measured in heat of combustion per unit of oxygen. Separating oxygen from air limits maximum efficiency, but has the advantage of requiring no new technology. ZECA-type plants offer one way to eliminate the high cost of producing oxygen. The other research strategy is to reduce the cost of oxygen and the associated energy penalty through advanced membrane or sorbent technology. If such an approach succeeds, plants that operate with pure oxygen may also become highly competitive.

Carbon Dioxide Capture from Air, Retaining a Carbon-Based Energy Market

Carbon capture on board a vehicle has been suggested as a means of addressing carbon dioxide emissions from fossil fuel–driven vehicles. Because carbon dioxide weighs three times as much as gasoline, this approach to carbon capture is very awkward and likely will remain extremely expensive. Instead one may want to consider recovering carbon dioxide directly from the air.

Currently the only practical form of air capture is photosynthesis in plants. It is well established, and at current levels of production it suggests a cost for carbon capture on the order of $30 per ton of carbon dioxide. Introducing alkalinity to the ocean prior to forming carbonates would effectively provide air capture as well, with the added benefit that there is no need to handle the captured carbon dioxide; sequestration and capture in this process are one and the same. On the other hand, the large dilution of the alkalinity prior to its introduction to the surface ocean would be a major cost driver for any such technology.

Engineered capture of carbon dioxide from the air with chemical or physical sorbents is certainly possible, but its cost effectiveness and practical viability still need to be demonstrated (Lackner et al., 1999). Various approaches seem feasible, but in essence all of them rely on air flow over or through a filter material that can absorb carbon dioxide out of the air. At first sight the scale of the flow channels may appear hopelessly large, but on closer inspection it can be shown that the scales are actually quite small. Consider the following examples: (1) at 370 ppm the carbon dioxide in the natural air flow through a coal plant's cooling tower carries with it roughly 25% of the amount of carbon dioxide emitted by the flue stack; (2) at reasonable wind speeds of 6 m/s, 22 tons of carbon dioxide per year (the per capita annual emission in the United States) flow through an opening of 0.2 m^2. Incidentally, at the same wind speed, the kinetic energy flowing per second through the same opening is 25W/m^2, or 0.25% of the per capita primary energy requirement.

A major challenge in the design of a good carbon dioxide extractor is the choice of a good sorbent. Although strong alkali or alkali-earth elements work well, they are corrosive and their binding energy to carbon dioxide is very high. Consequently the energy penalty for recycling the sorbent and freeing the carbon dioxide for subsequent sequestration become very high. Whereas gasoline per mole of carbon has 700 kJ of heat of combustion, the process of recovering lime from limestone requires approximately 200 kJ per mole of carbon. Even though this is a large energy penalty, it is in line with energy penalties expected in producing and storing hydrogen. However, the theoretical energy penalty for capturing carbon dioxide from the air due to the free energy of mixing is only 20 kJ/mole of CO_2. This is far smaller than the heat of calcination, raising the expectation that better sorbents could reasonably reduce the energy penalty by a factor of three or four.

Inasmuch as the air mixes rapidly, extraction of carbon dioxide from air effectively decouples energy production from sequestration. Emissions anywhere in the world can be recaptured at any location. The buffering capacity of the air is so large that decoupling can be accomplished not just spatially but also temporally. Carbon dioxide captured today could be counted against emissions that happened last month, or will happen next month without any significant change in atmospheric concentrations. This decoupling makes carbon dioxide extraction from air extremely interesting. It allows carbon dioxide recapture from cars, planes and other mobile or distributed sources. Because carbon dioxide can be captured at the site of carbon dioxide sequestration, the atmosphere transports the carbon dioxide from the point of emission to the disposal site for free. This opens up remote disposal sites, which would otherwise be inaccessible. Finally, carbon dioxide capture from the air can be introduced without the need of phasing out the existing energy infrastructure. Considering the lifetime of power plants and the fuel distribution infrastructure, which seem to last in excess of 50 years, this is an important consideration.

Because extraction of carbon dioxide from the air is not tied to emissions, it can ultimately be used to drive atmospheric levels of carbon dioxide downward. If the method proves viable for capturing a substantial fraction of all carbon dioxide generated in the consumption of fossil fuels, it should also be possible to increase the level of air capture beyond the point of carbon neutrality. Some time in the future, when carbon sequestration is fully implemented it would become possible to achieve a net negative carbon balance leading to the gradual reduction of atmospheric carbon dioxide concentrations.

Conclusions

Fossil fuel use will be limited by its environmental impact rather than by resource availability. The environmental impact of fossil fuels can be greatly ameliorated by carbon management technologies that capture carbon dioxide either at the source or from the air, and dispose of them safely and permanently. Technically, carbon management is already feasible on a limited scale, but in order to reach the scales that would be required for fossil fuels to retain a major role for at least another century, new technologies that only exist in a conceptual form will have to be realized in practical implementations. There is a hierarchy of possible strategies, and while a specific approach may run into difficulties, it appears unlikely that none of the technologies discussed could cope with the scale of the carbon management challenge. If an R&D effort to establish carbon management technologies proves successful, the resulting access to the vast reservoir of fossil energy allows sufficient energy for healthy economic growth not only in the developed countries but also in the developing countries. Fossil fuel use at a greatly expanded scale would be sustainable throughout the 21st century.

The goal of achieving, over the course of the next century, an average standard of living for the world that equals today's average standard of living in United States would be ambitious, but it becomes a worthwhile goal that the world could set for itself without running afoul of serious environmental or resource limitations. The current state of technology cannot support such economic growth without severe environmental impacts. Therefore new technological options will need to be developed. Sustainable development could go through an extended transition phase in which the energy supply remains dominated by fossil fuels. Eventually, fossil fuels may have to be phased out, but scenarios based on carbon management allow for ample time to develop practical and cost effective alternatives.

Carbon capture at large power plants allows for zero-emission designs. The value of the zero emission concept was first recognized in the chemical industry (Anastas and Kirchhoff, 2002). In order to survive, the coal-based power industry will have to embrace this concept, as the chemical industry has done before them. In such a vision, fossil fuels become an energy ore, from which clean energy carriers are extracted. These carriers include electricity and hydrogen. If capture from air is economically viable, clean energy carriers also include clean hydrocarbon liquids that would be desirable in a transportation sector that takes advantage of their excellent storage and handling properties and their extremely high energy density. As increased environmental concerns drive a trend to ultra-clean synthetic fuels, the distinction between different fossil fuel resources becomes less and less relevant, broadening the resource base and eliminating geographical imbalances in the world's fossil energy supply.

Without regulatory frameworks that make carbon dioxide emissions reduction either mandatory or economically advantageous, carbon management technologies cannot be implemented. The cost differential between ignoring carbon dioxide emissions and any other option, including sequestration, is too large to make purely voluntary action practical except in special circumstances. By internalizing the cost of carbon dioxide emission reductions, the cost of fossil fuel consumption will unavoidably rise. This will help level the playing field for non-fossil energy alternatives, whose price would not include a carbon sequestration cost. On the other hand it seems likely that even with the additional cost burden of carbon sequestration, fossil fuels will for some time provide the lowest-cost energy option.

Political frameworks for carbon management could develop through international collaboration and international treaties, or locally through grassroots actions. It seems that efforts in the United States are taking the latter route, as is witnessed by numerous actions on the state level. In either case, strategies should encourage technologies that can deal with the full scale of the required emission reductions. While the first implementations may only lead to small emission reductions, the path chosen should be compatible with the long-term goal of stabilizing carbon dioxide in the atmosphere. In the end, this means a nearly complete transition to carbon-neutral energy.

Given political support, carbon management technologies assure plentiful carbon-neutral energy for generations, giving non-fossil alternatives ample time to develop. Despite this optimistic outlook, it is important to realize that time is short to make the transition to carbon-neutral energy. Power plants that are being built today are quite likely still in operation by 2050. The financial risk of building a generation of stranded assets is rising with every year.

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