Part 1
Introduction and Overview

Process Engineering for CCS Power Plants, First Edition. Edited by Detlef Stolten and V. Scherer

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The Case for Carbon Capture and Storage

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Abstract

For a world of 10 billion people to achieve a decent standard of living, a prerequisite for political stability and a requirement for curbing population growth, society will need access to far more energy than it has today. Efficiency and conservation can reduce the growth in energy demand, but they cannot stop it. However, concerns over climate change will limit the use of fossil fuels. Fossil fuel consumption is the most important contributor to climate change because of the associated carbon dioxide emissions. While the oxidation of carbon is the unavoidable consequence of extracting energy from fossil carbon, the subsequent emission could be avoided by capturing the carbon dioxide and storing it permanently.

Keywords: carbon capture and storage, excess carbon, carbon reservoirs, storage capacity

1.1
Introduction

Economic growth and human wellbeing require access to plentiful energy. Even if energy efficiency and conservation can reduce the energy requirement for a given economic output, rapid world-wide economic growth is likely to overwhelm these reductions. Indeed, even most business-as-usual scenarios already count on the benefits of efficiency improvements, because they assume that the energy intensity of the world is improving at a rate of 1–1.5% per year [1]. With this assumption, the world's energy consumption, which grew by a factor of 12 in the last century, may only rise by another factor of 3–4 over the course of the twenty-first century.

Universal economic wellbeing is a prerequisite for political stability and apparently also for a gradual decline and ultimate stop of world population growth. Hence the world needs to find a way of providing the energy necessary to assure a decent standard of living for the 10 billion people expected to live

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on Earth in the second half of the century. This presents an enormous challenge. It is made much more difficult by climate change concerns, which put in question the continued reliance on fossil fuels. Today, fossil fuels provide about 81% of all commercial energy.

The avoidance of climate change demands the stabilization of the CO_2 concentration in the atmosphere [2]. One may debate the precise level at which stabilization will need to occur, but there is little doubt that a continued and unchecked rise in CO_2 concentrations is not sustainable. Stabilizing the atmospheric concentration of CO_2 at any reasonable level can only be accomplished by either abandoning fossil carbon as a source of energy, or by keeping the resulting CO_2 away from the atmosphere. Keeping the fossil carbon, once mobilized, out of the atmosphere requires some form of carbon storage. In effect, for every ton of carbon coming out of the ground, another ton of carbon will have to be returned. This is not a small task, considering that in the process of harnessing the energy of fossil fuels every ton of carbon is converted into 3.7 tons of CO_2.

As the wild swings in oil prices in the last decade have shown, even a small mismatch between supply and demand can lead to drastic price changes. Therefore, a forced abandonment of fossil fuels, which would lead to far more dramatic shortfalls in energy supply, could precipitate a major energy crisis. On the other hand, emission of CO_2 to the atmosphere will have to stop eventually.

Carbon capture and storage (CCS) technologies can assure access to the vast fossil carbon resources known to exist [3]. At a minimum, the world needs sufficient storage capacity to allow for a smooth transition from today's fossil carbon-based energy infrastructure to one that does not depend on fossil fuels. At the other extreme, a large storage capacity could render fossil carbon competitive even in a carbon-constrained world. With sufficient storage capacity, fossil fuel consumption could proceed until other limits, either from additional environmental impacts or from resource limitations, bring it to an end.

1.2
Dilution versus Treatment

The old adage, already criticized in the 1950s, that "the solution to pollution is dilution" [4] tends to work well with small effluents and large reservoirs. As effluent volumes increase, dilution becomes inefficient and waste processing and treatment become necessary. Sewage from cities and sulfur from power plants are two waste streams that have gone through such transitions from dilution to treatment. By contrast, CO_2 is still in the dilution stage. Treatment of this effluent lags behind the others because it is a non-toxic, colorless, odorless gas that occurs naturally in sufficient concentrations to mask emissions. Therefore, it requires a much larger effluent before problems will become visible.

After two centuries of fossil fuel use, dispersion of CO_2 in the atmosphere has found its limits because of climate change. The capacity of the atmosphere is not large enough to dilute the CO_2 to a level that avoids adverse consequences. The CO_2 concentration in the atmosphere is 40% higher than in preindustrial days, and unchecked it will double or triple before the end of the century. Dilution into the larger system of atmosphere, ocean, and biomass would alleviate the urgency of the problem, but would ultimately run up against the same limits [5].

Options for carbon storage include the dilution of CO_2 into the ocean, or a managed increase in biomass and soil carbon. Both options would buy some time. More permanent storage options include the formation of solid carbonates, which is known as mineral sequestration, or the injection of CO_2 into stable underground geological formations [6].

1.3
Carbon Reservoirs

At present, the concern over fossil fuel use is focused nearly exclusively on climate change, even though excess carbon in the environment also has other negative impacts. For example, excess CO_2 in the air results in higher concentrations of carbonic acid in the surface ocean and this acidification, in turn, is known to stunt coral growth [7, 8].

The air and the ocean are in close contact. Over time, the CO_2 transferred into the ocean migrates to deeper layers, reaching equilibrium throughout the entire water column in a few thousand years [9]. The carbon reservoirs in the ocean and the air are also tightly coupled to the carbon reservoirs comprising biological carbon in the form of living organisms and biological detritus mainly in the soil. The ocean, the world's biomass, and the atmosphere constitute a closely coupled set of carbon reservoirs that are remarkably self-contained. Although there is a large amount of flux between these pools, fluxes in and out of the larger pool are very small.

Emissions of CO_2 into the atmosphere result in a disequilibrium between these reservoirs and the carbon will gradually distribute itself between the ocean, the biomass, and the air. In the course of a century, about half of the CO_2 emitted will leave the atmosphere. On a millennium scale, equilibrium is achieved with 20% or more of the excess CO_2 staying in the atmosphere. The remainder will acidify the ocean. Over tens to hundreds of thousands of years, geological weathering processes will gradually remove excess CO_2 from the mobile carbon pool.

1.4
Excess Carbon

In short, one needs to consider the problem of CO_2 emissions from fossil fuels as a problem of excess in the world's mobile carbon stock. The excess is essentially permanent on a human time scale. On a time scale of less than a century, one can consider the atmosphere alone as a reservoir that will keep about half of the CO_2 that is injected.

The problem with emissions is that they accumulate. The environmental impact does not stop if emissions are halted; the size of the impact only stops growing. To a good approximation, the harm scales with the sum of all emissions over time, not with the rate of emission at a particular time.

Sustainability of fossil fuel consumption demands that the size of the mobile carbon pool is held in a range that avoids harm to the environment. As long as carbon is added to the pool, the CO_2 concentration in the air will increase and the ocean will acidify. Both changes have undesirable environmental consequences [2]. Stabilization of the CO_2 concentration in the atmosphere is possible only if emissions are reduced essentially to zero. The level at which stabilization is achieved will depend on the total amount of carbon that is mobilized and released to the atmosphere.

1.5
The Scale of Carbon Capture and Storage

The scope of the necessary CCS effort is defined by the gap between fossil fuel demand and allowable CO_2 emissions. The maximum acceptable level of CO_2 in the air or the maximum size of the mobile carbon pool is ultimately determined by policy decisions. Once this level has been reached, CO_2 emissions have to fall close to zero. Natural sciences can elucidate the consequences of elevated CO_2, but they cannot provide the value judgment necessary to determine what level is acceptable.

The acceptable upper limit of CO_2 in the air could be well below the current level. It has been argued by Hansen *et al.* [10] that breaching the 350 ppm level will destabilize the Greenland ice sheet and thus will result in unacceptable consequences. It is also possible that the value of 450 ppm, which has been embraced by European politicians, could still be acceptable. The acceptability of even higher levels cannot be entirely ruled out, even though they carry higher risks. Action is necessary, because business-as-usual scenarios could easily approach 1000 ppm before the end of the century [1].

No matter what the limit turns out to be, as the world approaches it, CO_2 emissions will have to be reduced towards zero. Hence continued use of fossil fuels will eventually require storing carbon at the same rate it is extracted from the ground. The question is not whether CO_2 emissions need to stop, but when they need to stop. The inertia in the world's energy infrastructure is such that even stopping at 550 or 650 ppm would suggest immediate action [11].

A stabilization level of 450 ppm would give the world another 60 ppm of uptake capacity in the air. Assuming that 50% of the CO_2 will remain in the air for a long time, this translates to a total carbon budget of 240 Pg ($1\ \text{Pg} = 10^{12}$ kg or 1 Gt), or slightly more than 30 t for every person on the planet. This should be compared with an annual consumption of 6 t per person in the United States.

The combination of population growth and rapid economic growth in the developing countries suggests that energy demand is likely to grow substantially, even with large improvements in the energy intensity of the world economy [1]. A world of 10 billion people consuming energy at the same rate as the United States, Canada, or Australia would consume energy at roughly 10 times the current rate. Therefore, large new sources of energy will be needed. Whether or not the use of fossil fuels with CCS remains competitive compared with other forms of energy is impossible to predict. The current cost differential between coal-based electricity, nuclear-based electricity, and wind- or solar-based electricity suggests that fossil fuels with CCS could plausibly compete with these technologies.

In summary, a scenario in which an annual storage demand in excess of today's emissions of 30 Pg per year could develop over the next 50 years is not implausible. On the other hand, it is not impossible that, for example, solar energy or nuclear energy will outcompete fossil fuels that are handicapped by cost of capture and the demand for an exceedingly large storage capacity. This, however, would require dramatic improvements in these technologies.

1.6
Storage Capacity Requirements

Storage capacity requirements are large, which makes CCS technology challenging. The amount of CO_2 that may need to be sequestered during the twenty-first century could easily approach 5000 Pg, which is equal to the amount of water in Lake Michigan. The current rate of emission is 30 Pg per year, which equates to 3000 Pg in the course of a century. Economic growth and population growth could easily combine to create a much larger output rate, which would need to be matched by capture if CO_2 is to be stabilized.

The known resource base of fossil fuels is even larger than any reasonable estimate of this century's consumption. Therefore, it is very unlikely that the growth of CO_2 emissions is self-limiting. Instead, it may well be necessary to prepare for the possibility that 5000 Pg of carbon is going to be mobilized over the course of a few centuries. If left unchecked, this would result in the emission of 18 000 Pg of CO_2.

In effect, the required storage capacity is set by the size of the available fossil fuel resource. Conservative planning would assume that given enough time, all available carbon may be used. Only time can tell how much of this carbon is actually accessible or affordable. Advances in technology are notoriously unpredictable [12]. It is not possible to predict the cost of natural gas from hydrates below the ocean floor in 50 years from now. It is equally difficult to predict whether coal seams 2000 m below the ground will remain unmineable. Neither the gas hydrates nor the deep coal seams are counted in today's resource estimate.

1.7
Conclusion

The case for developing CCS and implementing the technology on a large scale rests on a number of premises and observations:

- Energy is critical to human wellbeing. The availability of energy must be increased, even if energy efficiency and energy conservation measures can make the current energy supply go much further than it can go today.
- Energy can be clean. Environmental problems currently associated with energy are not the direct result of the consumption of energy but the unintended consequences of the specific ways in which energy is extracted from the ground, packaged, and delivered to the consumer. Changes in the energy infrastructure can reduce or even eliminate these problems. Today, the most pressing environmental challenge is the elimination of CO_2 emissions, which are associated with all uses of fossil energy.
- CO_2 emissions must stop. CO_2 emissions, or more broadly the problem of excess mobile carbon in the environment, is a stock problem, not a flow problem. Once the concentration of CO_2 in the air reaches the stabilization point, emissions have to be reduced essentially to zero. To a good approximation, the climate change constraint limits the maximum amount of fossil carbon that can safely be mobilized, for example, by releasing it as CO_2 into the atmosphere.

The rate of current CO_2 emissions combined with projections of growth under business-as-usual scenarios could easily triple the preindustrial level of CO_2 in the atmosphere before the century is over, and thus exceed any level that is considered safe and acceptable. Fossil fuel resources are large enough and fossil fuel technology is sufficiently developed that they could play a major role in providing for the world's growing energy demand. Solar energy and nuclear energy may be the only other energy sources large enough plausibly to provide a substantial fraction of world energy demand [11].

The stabilization of CO_2 in the atmosphere will require a revolution in the world's energy infrastructure. All future energy systems will have to operate in a carbon-neutral manner. There are very few options for achieving this goal. CCS is one of them. Because access to energy is vital, it is important to pursue the major options vigorously and not unnecessarily increase the risk of a major energy crisis.

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