# Capturing Carbon Dioxide From Air

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## Abstract

The goal of carbon sequestration is to take $CO_2$ that would otherwise accumulate in the atmosphere and put it in safe and permanent storage. Most proposed methods would capture $CO_2$ from concentrated sources like power plants. Indeed, on-site capture is the most sensible approach for large sources and initially offers the most cost-effective avenue to sequestration. For distributed, mobile sources like cars, on-board capture at affordable cost would not be feasible. Yet, in order to stabilize atmospheric levels of $CO_2$, these emissions, too, will need to be curtailed.

This paper suggests that extraction of $CO_2$ from air could provide a viable and cost-effective alternative to changing the transportation infrastructure to non-carbonaceous fuels. Ambient $CO_2$ in the air could be removed from natural airflow passing over absorber surfaces. The $CO_2$ captured would compensate for $CO_2$ emission from power generation two orders of magnitude larger than the power, which could have instead been extracted from the same airflow by a windmill of similar size. We outline several approaches, and show that the major cost is in the sorbent recovery and not in the capture process.

Air extraction is an appealing concept, because it separates the source from disposal. One could collect $CO_2$ after the fact and from any source. Air extraction could reduce atmospheric $CO_2$ levels without making the existing energy or transportation infrastructure obsolete. There would be no need for a network of pipelines shipping $CO_2$ from its source to its disposal site. The atmosphere would act as a temporary storage and transport system. We will discuss the potential impact of such a technology on the climate change debate and outline how such an approach could actually be implemented.

## Introduction

The economic stakes in dealing with climate change are big and costs could escalate dramatically, if the transition to a zero emission economy would have to happen fast. Abandoning existing infrastructure is prohibitively expensive and as long as new technology is not yet ready to be phased in, improvements and additions to the existing infrastructure will tend to perpetuate the problem. For this reason alone it is important to consider the possibility of capturing carbon dioxide directly from the air [1-4]. If capture from air would prove feasible, one would not have to wait for the phasing out of existing infrastructure before addressing the greenhouse gas problem. Technology for extracting $CO_2$ from the air could be deployed as soon as it is developed; it could deal with all sources of $CO_2$, and it even could be scaled up to reduce present levels of atmospheric $CO_2$. Deployment of air extraction technology need not interfere with other approaches to the problem. Avoidance of emissions, either through capture at a plant or switching to non-carbon based energy sources would still make sense, but one would not have to abandon existing infrastructure or construct a complex $CO_2$ pipelining system in order to get started. For the portion of the $CO_2$ that is emitted from small and distributed sources, capture of $CO_2$ from the air may always the best solution.

In this paper we argue that capture of $CO_2$ from natural airflow is technically feasible at a rate far above the rate at which trees capture $CO_2$. The photosynthesis by plants seems to be more limited by sunlight than capture of $CO_2$. We will provide a rough estimate of the expected cost and the scale of operation required to deal with the world's $CO_2$ emissions. Finally we will discuss the benefits of the approach and how this approach would fit into a no-regret strategy.

Until recently, the world has been concerned exclusively with the first half of the fossil fuel carbon cycle, i.e. with bringing the energy resource to the energy user. The waste $CO_2$ was simply abandoned to the atmosphere. With the growing understanding that the atmosphere is not an infinite sink comes the realization that carbon has not only to be moved from the well to the wheel but on from there to an appropriate sink, i.e. from well to a disposal site. Utilizing the air as a temporary buffer makes this process easier and avoids the need for developing specific capture processes for each and every emitter.

## Objective

If fossil fuels are to play a significant role through the 21st century, the accumulation of carbon dioxide in the air must be prevented. Current rates of fossil fuel consumption introduce an amount of carbon into the surface pool that over 100 years would match the size of the entire biomass. Unless painful actions are taken to reduce consumption, it is likely that world carbon consumption will grow rather than shrink. Natural processes are unlikely to absorb all this carbon, and $CO_2$ levels in the air will keep rising, unless $CO_2$ emissions are virtually stopped. To stabilize $CO_2$ levels, it is necessary to not only deal with $CO_2$ emissions from power plants, but from all sources in an industrial economy. While it is generally agreed that the reductions demanded by the Kyoto Treaty would be far less than what would ultimately be required to stabilize $CO_2$ levels in the atmosphere [5], it is also clear that even this goal would be too ambitious to be achieved by exclusively eliminating emissions from power plants. Since the economy and with it energy consumption have grown substantially since 1990, the reduction required in the United States is far more than the nominal seven percent reduction which is measured relative to 1990 emissions. The economy of 2010 would most likely have to reduce carbon emissions by more than 30% relative to business-as-usual. This is equivalent to eliminating all emissions from power plants. However, in the long-term carbon reductions will have to go far below 1990 emission levels and thus it is necessary to address all carbon dioxide emissions including those from small and mobile sources.

A portion of the desired reductions will be achieved by improved energy efficiency and energy savings, and another part might be accomplished by transition to non-fossil, renewable energy resources. However, here we concern ourselves with eliminating the remaining carbon dioxide emissions. Given the continuing and highly desirable worldwide economic growth, we expect this to be a large fraction of the total required emission reductions.

A source of carbon dioxide that is particularly difficult to manage is the transportation sector. A transition to electric or hydrogen fueled vehicles is in principle possible but would take a long time to accomplish. Even though it has been proposed [6], it does not appear to be economically viable to collect the carbon dioxide of a vehicle directly at the source. The mass flows would be prohibitively large. Generally, even stationary, small sources would be difficult to deal with. A unit mass of fuel results in roughly three mass units of gaseous $CO_2$ that would need to be temporarily stored at the source and later shipped to a disposal site. The mass of the stored material would be more than doubled once more, if one were to store the $CO_2$ absorbed onto some substrate, like CaO. Capturing $CO_2$ on board of an airplane is simply not possible because of the mass involved; in a car it would be prohibitively expensive; and even in a home it would not be practicable, as it would require a huge infrastructure for removal and transport of $CO_2$ to a disposal site.

Distributed carbon dioxide sources account for approximately half of the total emissions. While it may not be necessary to address them initially, for carbon management to be successful in the long term, they cannot be ignored.

Carbon dioxide capture from the atmosphere, in principle, can deal with any source, large or small. Indeed, the appeal of biomass for sequestration and of credits for growing trees is based on the very same premise. Since photosynthesis takes the carbon it needs from the air, it can compensate for any emission, and ideally it can be done at the disposal site eliminating the need for long distance surface transportation.

Thus, it is our objective to explore the feasibility of $CO_2$ capture from air. We would like to find out whether it is physically possible, whether it could be done at acceptable cost,and whether the scale of such an operation would be acceptable. We will show in the following that $CO_2$ capture is physically and economically feasible, and that the scale of operation is actually small compared to other renewable options that are considered as possible replacements for fossil energy.

## Approach

Carbon dioxide capture from air is certainly possible. Plants during photosynthesis routinely accomplish this task. Chemical processes also can capture $CO_2$. A classic chemistry experiment is to bubble air through a calcium hydroxide solution and to remove the air's $CO_2$ in this fashion. Other means work as well and have been used in the past in industrial processes to generate $CO_2$ free air. However, in capturing $CO_2$ one is very much constrained by economic considerations. One can hardly spent any effort in handling the air as any cost is amplified by the dilution ratio, which is roughly one part in three thousand.

It is not economically possible to perform significant amount of work on the air, which means one cannot heat or cool it, compress it or expand it. It would be possible to move the air mechanically but only at speeds that are easily achieved by natural flows as well. Thus, one is virtually forced into considering physical or chemical adsorption from natural airflow passing over some recyclable sorbent [1, 2]. Once the $CO_2$ has been taken out of the air, the down stream processing deals with volumes and masses that are of the same order of magnitude as the $CO_2$ itself and is therefore not subject to the large amplification factor that results from the dilute nature of $CO_2$ in air.

To get an appreciation for the scales, let us measure the $CO_2$ content of air in energy units. At 365 ppm of $CO_2$ in the air, a cubic meter (or 40 moles of air) contains 0.015 moles of $CO_2$. If this $CO_2$ were extracted from the air to compensate for an equivalent $CO_2$ emission by a gasoline engine somewhere else, we could relate the amount of $CO_2$ in a cubic meter of air with the heat released in the combustion of gasoline resulting in the emission of the same 0.015 moles of $CO_2$. This heat of combustion amounts to 10,000 J. Thus removing the $CO_2$ from one cubic meter of air and disposing of it opens the door for generating 10,000 J of heat from gasoline anywhere in the world. Combined, these two actions are carbon neutral.

This approach to a net zero carbon economy works, because $CO_2$ in the air is not harmful and the natural amount in the air is large compared to the amounts human activities add on short time scales. Current annual world emissions from human activities equal 1% of the total $CO_2$ in the air. Since mixing times are far shorter than a year, one can use the air as a conveyer that moves $CO_2$ from its source to its sink. As long as the total amount in transit is small compared to the air's $CO_2$ content, moving $CO_2$ in this fashion to the sink would not unduly distort atmospheric $CO_2$ concentrations. Locally, mixing is very fast and therefore local $CO_2$ depletion or enrichment is not likely to pose a problem either. If this were not the case, emissions from power plants would cause large local deviations. In the same fashion as $CO_2$ enriched air mixes rapidly with ambient air to maintain constant levels of $CO_2$, air depleted in $CO_2$ will also mix rapidly and return to ambient conditions. It is, however, this mixing rate which sets the limit of how closely one could space $CO_2$ extraction units [2, 4].

We note that the $CO_2$ content of a volume of air, as measured by the heat of combustion its removal could compensate for, is far larger than the kinetic energy the same volume of air would have assuming reasonable wind velocity. At 10 m/s, which is a wind stronger than is usually assumed to prevail in windmill operations [7], the kinetic energy of a cubic meter of air is 60 J, which should be compared to 10,000 J for the heat of combustion that would generate the $CO_2$ content of a cubic meter of air. A windmill that operates by extracting kinetic energy from natural airflow needs to be two orders of magnitude larger than a $CO_2$ collector that captures $CO_2$ to compensate for the emissions from a diesel engine that generates the same amount of electricity. Since windmills appear economically viable, this suggests that the capturing apparatus should not be too expensive to build.

One can pursue this line of reasoning a little further by looking at the same data in a slightly different fashion. Windmills are rated by energy flux per unit area. In effect the wind carries with it a flow of kinetic energy, a part of which a windmill transfers into electric energy. Thus a windmill at wind speed of 10 m/s would face an energy flux of 600 $W/m^2$. The equivalent $CO_2$ flux through the same area corresponds to 100,000 $W/m^2$. Thus an air "filtration" system could extract $CO_2$ from a stream that represents power generation of 100,000 W for every square meter of airflow. By this measure, $CO_2$ is far more concentrated than the kinetic energy harnessed by the windmill.

By invoking a measure of power per unit area we can also compare the efficacy of our approach to collecting solar energy. Peak fluxes of solar energy on the ground are around 1,000 $W/m^2$. Average fluxes in desert climates accounting for weather and day and night are around 200 $W/m^2$. Photovoltaic panels can capture maybe 25% of this flux. Under conditions of intensive agriculture, biomass growth can capture maybe 1.5% of this flux, and thus would rate at roughly 3 $W/m^2$ [8]. Typical unmanaged forest growth would fall far short of capturing even that much carbon equivalent.

The purpose of this discussion is to establish an estimate of a system's size necessary to collect $CO_2$ generated by an energy source of a given size. If one could maintain a flow of 3 m/s through some filter system, and collect half the $CO_2$ that passes through it, then the system would collect per square meter the $CO_2$ output from 15 kW of primary energy. This is more than the per capita primary energy consumption in the US, which is approximately10 kW. The size of a $CO_2$ collection system would thus have to be less than $1m^2$ per person. Covering the same energy demand with wind-generated electricity instead would require an area at least a hundred times larger.

Even before having defined specific filters and sorbent materials, this discussion already suggests that the cost of $CO_2$ collection is not prohibitively high. Prior to any specific designs, let us assume that in collecting $CO_2$ from a natural airflow, one needs equipment that is different from but similar in size and cost to what one would use for a windmill harvesting wind energy from the same cross sectional flow area. We furthermore assume that both systems have the same capture efficiency. If the cost of a windmill operating on wind speeds of 6m/s is 5¢/kWh, then the equally sized $CO_2$ collector will collect 100 kg of $CO_2$ for every kWh its windmill partner collects.[1] Thus, according to this simple comparison, the capture process should add 50¢ to the cost of a ton of $CO_2$. Of course this estimate is very crude, but even if the actually implementation were 5 times more expensive, the basic argument would not be affected.

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[1] The above comparison is straightforward: At 6m/s one finds that through the windmill collection area pass $130W/m^2$ of kinetic energy carried by the air. Through the $CO_2$ collector pass $3.8g/(m^2 sec)$ of $CO_2$. In an area and time in which the windmill collects 1 kWh the $CO_2$ collector of equal efficiency extracts $3.6\times10^6$ J/130 J×3.8 g = 105 kg. Thus collection of 1 ton of $CO_2$ is equivalent to the generation of 10 kWh of electricity from wind.

However, the cost of contacting the air and scrubbing out the $CO_2$ is not the only cost one needs to consider in extracting $CO_2$ from air. For most sorbents that could have captured the $CO_2$ one needs to recover the sorbent and release the $CO_2$ in a concentrated stream ready for disposal. These process steps are likely to be far more expensive than the capture itself. Processing a ton of material tends to be measured in dollars not cents. Using cement manufacture to set the scale for this cost, Gilberto Rozenchan arrived at a price on the order of \$10 to \$15 per ton of $CO_2$. Even at this price, the approach would have great promise, in that it would allow capturing the $CO_2$ from gasoline for 9¢ to 14¢ per gallon of gasoline. For comparison, the cost of the crude oil (\$30/barrel) going into the generation of one ton of $CO_2$ amounts to \$80.

Thus, we need to develop a technology that would allow the capture of $CO_2$ from natural or man-made airflows that would enable us to recycle the sorbent and create a concentrated stream of $CO_2$. In the following section we shall discuss options for such processes.

## Technology

A collector capturing $CO_2$ from a natural airflow is akin to a windmill. In one case one extracts $CO_2$ out of the airflow, in the other case one extracts kinetic energy. However, one should not pursue this analogy too far. A modern windmill has an aerodynamic design that maximizes momentum flow from the air to the airfoil. Unlike momentum that can be transported independently of mass flow, material flows are intimately tied to mass flow and thus require drastically different designs. The first task in developing $CO_2$ capture from air would be to define an optimal design. Candidates include filter banks standing in the airflow like snow fences, designs that resembles leaves on a tree, or systems akin to cooling towers that actively move the air.

To illustrate this with an example: some years ago, a wind energy technology was suggested that could operate in a dry climate. Inside a large tower, water is pumped to the top, where it cools the air by evaporation. The cold air, being denser, would cause a downdraft inside the convection tower. The potential energy of the air falling down is eight times larger than the potential energy of the water that has to be pumped up. The air flows through the lightweight

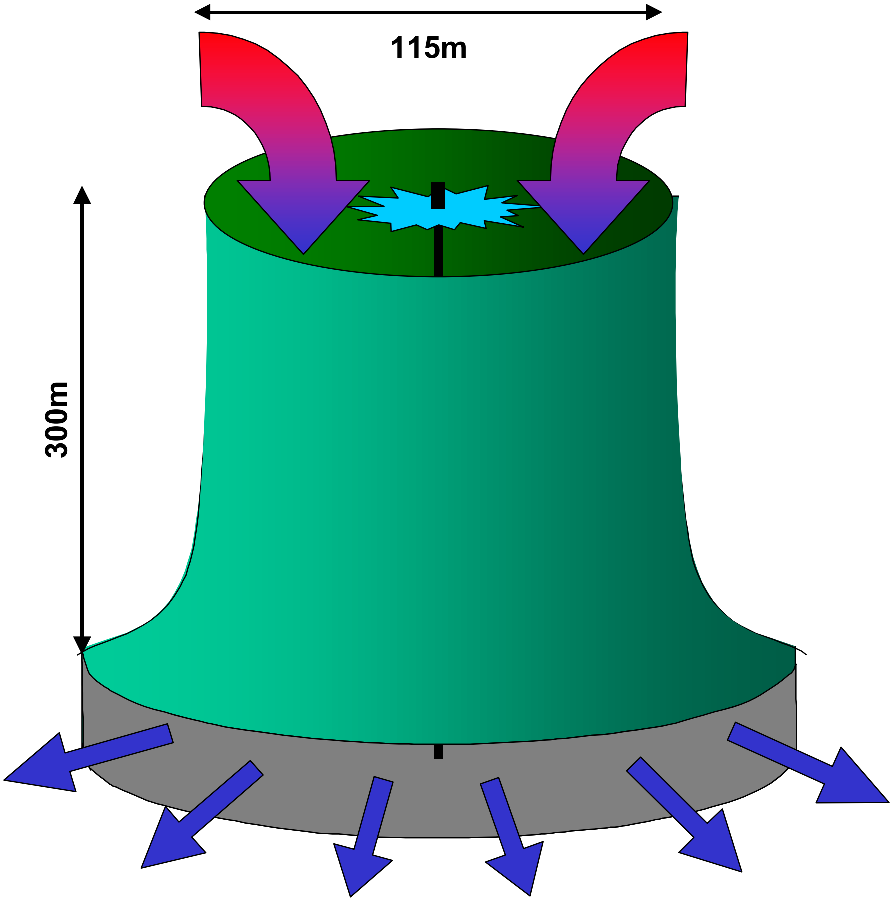

**Figure 1:** Sketch of a convection tower that could either provide electricity or $CO_2$ capture. Water pumped to the top cools the air, which causes a downdraft inside the tower. The tower has a 10,000 $m^2$ opening. Cooling the air to the degree possible in a desert climate would cause in the absence of obstructions a downdraft in excess of 15 m/s generating a flow of nearly 15 $km^3$ of air per day through the tower. The air leaving at the bottom could drive wind turbines or flow over $CO_2$ absorbers. Based on the volumes of air flowing and the potential energy of the cold air generated at the top of the tower, the tower could generate 3 to 4 MW of electricity after pumping water to the top. The same airflow would carry 9,500 tons of $CO_2$ per day through the tower. This $CO_2$ flow equals the output of a 360 MW power plant.

tower structure and escapes at the bottom where its kinetic energy is harnessed by a number of wind turbines. This effort had grown from preliminary designs to a consortium that was planning on building such a tower in the Negev desert [9]. For such a tower to be economically viable it would cost maybe \$3,000 per $kW_e$. Such a cost does not appear unreasonable. Nevertheless in the end, these towers were not built. However, our point here is only to show how much more efficient such a tower would be at extracting $CO_2$ rather than kinetic energy.

Figure 1 shows a simple design of a convective tower that would generate 3 to 4 MW of electricity. It also passes 9,500 tons/day of $CO_2$ through itself, which corresponds to the $CO_2$ output of conventional 360 MW coal fired power plant. The $CO_2$ flux is also equivalent to the $CO_2$ output of the vehicle fleet of a city of 700,000 people, indicating the usefulness of the concept for dealing with emissions from the transportation sector. The first comparison to the coal-fired power plant reiterates our earlier observation. The cost of the collection tower, even if it exceeded the \$9 million implied by a cost of \$3,000/kW for its electricity generating cousin, would still be extremely cheap compared to the cost of the coal fired power plant, which would be approximately \$300 to \$400 million. Thus, the cost of the collection tower would be dwarfed by the cost of the corresponding power plant. While we are not advocating this specific design for $CO_2$ capture, it shows once again that the physical structure required to capture the $CO_2$ is not going to drive the cost of the process. There are a number of different design options, and further work will have to tell which ones are most advantageous.

If we make the assumption that sorbents can be found, which are chemically reactive and have equilibrium partial pressures of $CO_2$ over them that are substantially lower than ambient partial pressures, then one can estimate what sizes of filters will be needed to collect a substantial fraction of the $CO_2$ in the air passing through. As a simple proof of principle we consider a slurry and solution of $Ca(OH)_2$. For such slurry the rate of reaction is reasonably fast, and the partial pressure of $CO_2$ would substantially lower than ambient partial pressure in air. We have performed a more detailed analysis elsewhere [2] and only note here that the diffusion of $CO_2$ through air is for many designs the rate limiting step. We found that surfaces with square millimeter orifices and passage length of a few centimeters would remove most of the $CO_2$ from laminar airflow. Thin absorbing threads like in conventional air filters may be even more advantageous and would allow for lighter structures. Details of such designs would have to await the choice of sorbent, e.g. whether it is liquid or solid, as such details would have direct influence on the specific choice.

The choice of sorbent needs to be carefully considered. Calcium hydroxide is an obvious candidate for a sorbent, but it is likely that there are better choices. For one, the binding energy of the carbonation reaction of calcium hydroxide or calcium oxide is far larger than would be required on thermodynamic grounds. The free energy penalty of concentrating $CO_2$ to 1 bar is RT log $P/P_0$. Where $P_0$ is 1 bar and P is the ambient partial pressure of $CO_2$. At ambient temperatures this number is approximately 20 kJ/mole. In the case of CaO, the binding energy is 180 kJ. For $Ca(OH)_2$ the penalty at 120 kJ is somewhat lower, but it would be very difficult to avoid a transitional step which makes lime from lime stone before the lime is slaked.

A good sorbent should not escape in large quantities from the capturing system, and it should be environmentally benign. It needs to be either extremely cheap, or can withstand many recycle loops.

## Results

Results of our dimensional analysis suggest that the collection of $CO_2$ directly from air is feasible. Collecting $CO_2$ from air is far more efficient than collecting wind energy. We emphasize that we can make this statement without having determined an optimal collection system or having settled on an optimal choice of sorbents. Even looking at the most simple implementations suggests that the cost of the effort is tolerable. Our simple analysis suggests, that filter systems using alkaline solutions of $Ca(OH)_2$, or sodium or potassium hydroxide could easily capture $CO_2$ from air. The major cost of any such process is in the recovery of the sorbent. A preliminary analysis assuming $Ca(OH)_2$ as a possible sorbent suggests, that the cost will be on the order of \$10 to \$15 per ton of $CO_2$ and that the additional $CO_2$ generated in the process of collection is substantially less than the amount of $CO_2$ captured. In any event, one would design the sorbent recovery system so that it would capture its own $CO_2$. Since this process would be a large operation at a good disposal site, it is a prime candidate for on-site capture. The energy penalty for this approach is about 200 kJ for every 700 kJ of heat of combustion from gasoline. Per gallon of gasoline one would need 3 cents worth of coal to accomplish the $CO_2$ recovery from lime. Other sorbents, with better chemical kinetics and lower binding energies could substantially improve the cost of the overall process design.

We have also looked at the overall scale of the collection effort. As mentioned earlier, the cross sectional area needed in the US is slightly less than 1 $m^2$ per person. However, one could not combine all these units in a single location, as they would tend to interfere with each other. Units down wind from other units could not capture the nominal value of $CO_2$ as they would be processing air already depleted in $CO_2$.

What limits the amount of $CO_2$ one can remove from airflow in one location is the rate of turbulent diffusion from higher altitude to the ground. A recent study [4] suggests that the overall rate of uptake is indeed what one would expect from turbulent diffusion coefficients that are on the order of $10m^2/s$.

Even a worldwide collection system does not have to be extremely large. Per person the cross sectional area facing the wind would have to be about $0.12m^2$. The area would increase $0.65m^2$ per person if the world's *per capita* energy consumption would reach the current US *per capita* consumption. At present rate, 380,000 collection units eaching taking up 100 m × 100 m in land area could collect all the $CO_2$ emissions from human activities. One would need one such unit – roughly two football fields – for every 16,000 people. These units could share the land with other activities. For example each unit could consist of 5 vertical subunits 19 m wide by 19 m tall. The 380,000 units would have to be spread out over an area at least 530 km by 530 km of which they would occupy 1.4%.

## Benefits

The method of extracting carbon dioxide from the air we outlined above could operate on a scale large enough to deal with all the carbon dioxide emitted in the world. The only limit to the use of this approach would be from other technologies that for specific emissions may be more cost-effective. One advantage of extraction from air is that it would be possible to sequester more $CO_2$ than is generated, thereby reducing the total $CO_2$ load of the atmosphere.

Quite likely, in the long term one would limit extraction from air to the capture of $CO_2$ from distributed sources and to excess $CO_2$ already in the air. If included into the design from the start, the collection of $CO_2$ at a concentrated source is always cheaper than first letting the $CO_2$ dilute in the air and recapture it later. There are, however, additional issues to consider. One is the cost of transporting $CO_2$. Transport by the air comes free, and typical cost estimates for long distance transport of $CO_2$ are around $10/ton. At that cost, a careful economic analysis would be required to decide whether in a given case atmospheric convection would not allow for a cheaper solution to the problem. The cost of carbon capture could well be comparable to the cost of shipping carbon. Furthermore, extraction from air would open up resource sites for carbon disposal, which are simply too far away from all sources to compete by any other means. This additional effect may well compensate for a slightly higher cost in capture relative to transport to a more nearby sink.

Consider some examples: Disposal in the deep ocean would only be feasible from a platform at the disposal site. In this case, $CO_2$ capture on site, may well be cheaper than $CO_2$ shipping from distant harbors. Secondly, just like some of the best oil reservoirs turn out to be in remote locations, some of the best underground deposits for $CO_2$ may also be in isolated locations. Again, it may be easier to serve such sites by extracting $CO_2$ from air rather than shipping it over long distances. Finally, many sites for successful mineral sequestration would again be in remote sites, as for example in Alaska or the Canadian Northwest.

For mineral carbonate disposal, remoteness would facilitate mining. The overall area affected by mining is not very large, but mining in or near populated areas is problematic. On the other hand, sites in remote locations would not be useful, unless the $CO_2$ is directly taken from the air.

As we mentioned in the introduction, a major advantage of carbon capture from the air is that it does not require abandonment of existing infrastructure. Extraction from the air could be introduced in parallel to other methods that sequester carbon dioxide directly captured at the source. It would allow the removal of $CO_2$ virtually immediately and it could be grown rapidly over the course of the next few decades. The cost of the process is independent of the amount of consumption. While on-site capture becomes more and more expensive as one is trying to drive emissions to zero, net-zero emissions obtained by matching extraction from air to the output of some plant, does not incur such increases in cost. Indeed one could aim for 80%, 100% or even 120% capture without substantively changing the cost structure. By having capture exceed emissions, one could actually aim for reducing $CO_2$ in the air.

How fast such a method will be introduced depends on many variables. If we assume that the overall cost of the process is $15 per ton of $CO_2$ and if we further assume that roughly half of this cost is in capital investment, then the elimination of 22 billion tons of $CO_2$ would represent an annual cost of $330 billion worldwide. The capital cost involved would be on the order of 1.6 trillion, which is a huge number, but it is again not so large as to be prohibitive. If one were to aim at an implementation in the course of a decade, the total worldwide capital investment would be comparable to the current discussion on tax cuts in the US alone. New industries like the electronic industry have shown that investments on this scale can indeed be made in a matter of decades. Whether or not it will be done depends on the perceived urgency of the problem.

## Future Activities

To move from a simple dimensional analysis to a full development of the technology, a number of R&D issues will need to be addressed. One is the modeling and understanding of the airflow in order to define the maximum level of $CO_2$ that can be removed at any given site without untoward side effects. Preliminary studies suggest the feasibility of the approach in this regard [4].

Secondly, one needs to choose between various designs for contacting natural airflows. The situation is right now wide open and somewhat reminiscent of the early days in windmill design. Many vastly different designs competed with each other until finally a handful of particularly elegant and simple solutions took over.

Thirdly one needs to find a good sorbent. Currently the only sorbent that is environmentally acceptable and guaranteed to work is $Ca(OH)_2$. Other possibilities will need to be explored.

We are planning the analysis of several process implementations for the extraction of $CO_2$ from air. A successful process design, combined with any of the methods proposed for carbon dioxide disposal would be a major step toward solving the greenhouse gas problem and toward establishing a net zero carbon economy that would not have to abandon the vast fossil energy resources that could fuel economic prosperity for generations.

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