Air Capture and Mineral Sequestration

Tools for Fighting Climate Change

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Summary

Thank you for giving me the opportunity to express my views on air capture and mineral sequestration, two of the technologies that are included in this hearing as geo-engineering approaches to climate change.

Together, air capture and mineral sequestration provide a comprehensive solution to combat climate change. Capturing carbon dioxide from the air and storing it safely and permanently as solid mineral carbonate provides a way to maintain access to plentiful and affordable energy, while stabilizing the carbon dioxide concentration in the atmosphere. Abandoning fossil fuels would seriously affect energy security. On the other hand, the continued emission of carbon dioxide would have harmful consequences for climate, oceans, and ecosystems. Air capture can extract unwanted carbon from the atmosphere, and mineral sequestration can provide a virtually unlimited and safe reservoir for the permanent storage of excess carbon.

Introduction

Stabilizing the concentration of carbon dioxide in the air requires reducing carbon dioxide emissions to nearly zero. Think of pouring water into a cup; as long as you pour water into the cup, the water level in the cup goes up. It does not matter whether the maximum level is one inch below the rim or one and half inches below the rim. In either case, you will eventually have to stop pouring.

Stopping or nearly stopping carbon dioxide emissions cannot be achieved with energy efficiency and conservation alone. These steps will slow the rate of increase but will not prevent us from eventually reaching the top of the glass, so to speak. Unfortunately, there are only a few choices for energy resources big enough to satisfy future world energy demand. Solar, nuclear and fossil energy are the only resources large enough to let a growing world population achieve a standard of living that we take for granted in the United States. Eliminating fossil fuels from the mix could precipitate a major energy crisis. Thus, it is critical for us to maintain all options by developing technologies that allow for the use of carbon-based fuels without leading to the accumulation of carbon dioxide in the atmosphere.[1]

The goal of a perfectly carbon neutral energy economy is only a slight exaggeration of what is needed; only a small and ever decreasing per capita rate of emissions is compatible with a constant concentration of carbon dioxide in the atmosphere. For the developed countries, this means reductions in the carbon intensity of their energy systems by much more than 90% by some point in this century. Without such reductions, the world would have to settle for far less energy, or an uncontrolled rise in the carbon dioxide concentration of the atmosphere. This is true whether the world succeeds in stabilizing the carbon dioxide concentration in the air at the currently suggested level of 450 ppm, or fails and ends up stabilizing at a much higher level some decades later. In my view, a transition to a carbon neutral economy is unavoidable. The question is only how fast we will be able to stabilize the carbon dioxide level in the atmosphere, and what pain and what risk the world will accept in exchange for a less rapid transition.

Capture of carbon dioxide from the air and mineral carbonate sequestration are two important tools in stabilizing carbon dioxide concentrations without giving up on carbon-rich energy sources and carbon-rich fuels like gasoline, diesel, or jet fuel. While this committee is considering air capture and mineral sequestration in the context of geo-engineering, these technologies are very different from other geo-engineering approaches like albedo engineering or ocean fertilization technologies. They involve far less risk, because they do not attempt to change the dynamics of the climate system, but simply return it to a previous state. Air capture and mineral sequestration simply work towards restoring the carbon balance of the planet that has been disturbed by the massive mobilization of fossil carbon. Their purpose is to capture the carbon that has been mobilized and to immobilize it again. Because they function within the existing carbon cycle, they also have far fewer unintended consequences than many other geo-engineering approaches.

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[1] For a more detailed discussion see Lackner, K. S. (2010), Comparative Impacts of Fossil Fuels and Alternative Energy Sources, in *Issues in Environmental Science and Technology: Carbon Capture, Sequestration and Storage*, edited by R. E. Hester, and R.M. Harrison, pp. 1-40.

Air capture removes carbon dioxide directly from the air. It therefore can compensate for any emission, even emissions that happened in the past. We could theoretically reduce the atmospheric level of carbon dioxide to the pre-industrial level (280 ppm) while continuing to use fossil fuels. Mineral sequestration closes the natural geological carbon cycle and immobilizes carbon dioxide by forming stable and benign minerals. Both technologies fall into the broader category of carbon dioxide capture and storage. Among these technologies, they stand out because they are comprehensive. Air capture could cope with all carbon dioxide emissions; mineral sequestration could store all the carbon that is available in fossil fuels.

Without carbon dioxide capture and storage, the only way to stabilize the carbon dioxide concentration of the atmosphere is to abandon coal, oil and natural gas. As previously discussed, this option is, in my opinion, not viable or practical. Carbon dioxide capture and storage technology offers a way to maintain access to this plentiful and cost-effective energy source, while addressing the biggest environmental downside associated with their use.

In my view, carbon dioxide capture and storage pose two major challenges: how to catch the "fugitive" emissions that are not amenable to capture at the source of emission and how to deal with the vast amounts of carbon dioxide that will need to be stored safely and permanently.

Air capture can address the myriad emissions from small emitters including cars and airplanes and also deal with the last few percent of power plant emissions whose escape is expensive to prevent. Other capture options may be advantageous for particular situations, e.g., in the flue stack of a power plant, but air capture can assure that all emissions can be dealt with.

Storage of carbon dioxide is difficult. Since carbon dioxide is a gas, it will tend to escape from its storage site unless it is chemically converted to a mineral. Over this century, the mass of the carbon dioxide that will need to be stored will rival the amount of water in Lake Michigan. To avoid the escape of the carbon dioxide back into the atmosphere, it becomes necessary to maintain a physical barrier between the gas and the atmosphere, and to assure its efficacy for thousands of years. Given the large volumes involved, this raises serious questions about the safety and permanence of underground gas storage. These questions can only be answered by considering the specifics of each particular site. Quite rightly, the public will demand a careful risk analysis and detailed accounting, which will result in a gradual reassessment of the overall capacity of geological storage. I consider it likely that current estimates are too optimistic. Nevertheless there will be significant and adequately safe underground storage of carbon dioxide gas because there are some excellent storage sites available, and the technology to use them already exists. However, mineral sequestration may be required to complete the task of carbon sequestration on a longer time scale. Mineral sequestration converts the carbon dioxide chemically into a solid mineral that is common and stable in nature. There is no possibility of a spontaneous return of the carbon dioxide. Even though mineral sequestration may be more expensive up front, its long-term costs may prove to be more affordable.

Air Capture

The ability to capture carbon dioxide from the air is not new. Every submarine and every spaceship needs to remove carbon dioxide from the air inside in order to keep the crew healthy. The challenge is not to capture carbon dioxide from the air, but to do so in an economically affordable fashion and on a large scale.

I was the first to suggest that capture of carbon dioxide from the air should be considered as a promising approach to managing carbon dioxide in the atmosphere and hence to combating climate change. [2] Capture from the atmosphere has many advantages. First, it separates carbon dioxide sources from sinks, so it makes it possible to collect carbon dioxide anywhere in the world. Air mixes so fast and so thoroughly that capture in the Nevada desert could compensate for emissions in New York City, in Mali, in Ghana, or anywhere in the world. In a matter of weeks to months after starting to capture carbon dioxide in the Northern Hemisphere, the carbon dioxide reduction will have spread out over the entirety of this hemisphere.

Before starting research in this field, I was struck by two observations that suggested technical feasibility. First, the concentration of carbon dioxide in the air, although usually considered very small, is by some measure surprisingly large. To illustrate this point, consider a windmill, which can be viewed as an apparatus to reduce the human carbon footprint by delivering electricity without carbon dioxide emissions. For the same amount of electricity from a conventional power plant could be made carbon neutral with a carbon dioxide collector. The frontal area of this collector standing in the wind could be more than a hundred times smaller than that of a windmill. This convinced me that the cost of scrubbing the carbon dioxide out of the air is not in the apparatus that stands in the wind, but rather it is in the cost of "scraping" the carbon dioxide back off collector surfaces, so they can be used again. Fortunately, the binding strength of these sorbent surfaces need not be much stronger than the binding strength of the sorbent materials that would be used in a flue stack to scrub the carbon dioxide out of the flue gas. This fact, which follows from basic thermodynamics, is surprising considering the three hundred times higher initial concentration of carbon dioxide in the flue gas stream versus in the atmosphere. These insights – based on fundamental physics and thermodynamics – led me to start a large effort in air capture research, which has been funded by Gary Comer, the former owner of Lands End. Much of the work has been performed at a small research company (Global Research Technologies) of which I am member, a fact that I feel obligated for reasons of transparency to disclose. Much of the research effort is now housed at Columbia University.

This original R&D effort allowed us to go beyond theoretical arguments of what could be done with some ideal sorbent materials. We were able to demonstrate our ability to capture carbon dioxide from the air with real sorbents that require very little energy both in their regeneration and in the preparation of a concentrated stream of carbon dioxide ready for sequestration. We discovered a novel process, which we refer to as a moisture swing absorption system. We create air scrubbers that load up with carbon dioxide when dry and then release the carbon dioxide again when exposed to moisture.

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[2] K.S. Lackner, H.-J. Ziock, and P. Grimes (1999), Carbon Dioxide Extraction from Air: Is It an Option?, presented at Proceedings of the 24th International Conference on Coal Utilization & Fuel Systems, Clearwater, Florida, March 8-11, 1999.

We have demonstrated the capabilities of this sorbent in public and have published our results.[3] In short, our system requires water and electricity to collect carbon dioxide. The water can be saline and the energy consumption of the process is such that only 21% of the carbon dioxide captured would be released again at a distant power plant that produces the electricity required in the process.[4] Nearly 80% of the captured carbon dioxide counts toward a real reduction of carbon dioxide in the atmosphere. At this point we have demonstrated the system on the bench scale, and are moving toward a one-ton-per-day prototype. Just like a hand-made car will be expensive we expect a first of a kind version to capture carbon dioxide at approximately $200 per ton. This cost is dominated by manufacturing and maintenance cost and we see significant and large potential for cost reductions. We have set ourselves a long term goal of $30/ton of carbon dioxide, or roughly an addition of 25¢ per gallon to the price of gasoline. While we are not the only ones developing air capture technology, we were the first to get started, and we believe we are the closest to viable solutions.

Technical air capture, as opposed to growing biomass in fields, in forests and in algae ponds, can operate with a much smaller footprint. A "synthetic tree," our mechanical device to capture carbon dioxide from the air, collects approximately a thousand times as much carbon dioxide as a natural tree of similar size. It is for this reason that air capture is of practical interest.

Just as there are proposed side benefits to industry and the economy from bio-mass management of carbon dioxide, there are several immediate applications for carbon dioxide captured from the air. First, there is a small market of eight million tons per year for merchant carbon dioxide (i.e., carbon dioxide that is shipped by truck to its customers). Applications range from dry ice production to welding supply and carbonation of drinks. The price of merchant carbon dioxide depends on the distance from the nearest source and is often well above $100/ton. This market could provide a toehold for air capture technology where it could be tested before carbon regulations address climate change issues. Oil companies provide another potential market for air capture. In the United States some forty million tons of carbon dioxide are consumed annually in enhanced oil recovery.

In the future one can expect a large market for air-captured carbon dioxide in managing carbon for climate change. Total emissions in the United States are nearly six billion tons of carbon dioxide per year. Some fraction – currently nearly half – of all emissions comes from sources that do not lend themselves to capture at the point source. These include emissions from automobiles and airplanes. Indeed, practically all emissions from oil consumption fall into this category. As a result, air capture is the only practical option to maintain access to oil-based energy products. Indeed, mitigating the use of liquid hydrocarbon fuels is an important application for air capture. There is no good alternative to liquid fuels, e.g., gasoline, diesel or jet fuel. A pound of fuel contains about one hundred times as much energy as a pound of battery.

Air capture remains necessary as long as liquid carbon-based fuels are used in the transportation sector. Regardless of the carbon source in the fuel, the carbon will end up as carbon dioxide in the air, which will need to be captured. Rather than storing the carbon dioxide, it is also possible to recycle its carbon

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[3] Lackner, K. S. (2009), Carbon of Dioxide Capture from Ambient Air, *The European Physics Journal: Special Topics*, *176*(2009), 93-106.
[4] The 21% is based on the average CO_2 emissions in US electricity generation.

back into fuel, but this way of closing the carbon cycle requires renewable or other carbon-free energy inputs. Biomass fuels are a special example of closing the carbon cycle. Green plants capture carbon dioxide from the air by natural means and with the help of sunshine convert it into energy rich carbon compounds. However, the ability of biological systems to collect carbon dioxide from the air is slow. Thus, large-scale fuel production requires large swaths of land. Indeed, algae growth is limited by the innate ability of algae to collect carbon dioxide. And many companies have realized that they could improve performance by providing carbon dioxide from other sources. This could be carbon dioxide from a power plant, but ultimately one can only close the global carbon cycle if this carbon dioxide comes directly from the air. Air capture would be a natural complement to algae production of synthetic fuels.

Air capture can work for any emission of carbon dioxide, no matter where it occurs. Thus, it can provide the capture of last resort. For most power plants, capture at the site is the most economic approach, but in a number of older plants, it may be cheaper to collect carbon dioxide from the air or to install scrubbers that can only partially remove the carbon dioxide in the flue stack. The remaining fraction would still be released to the air and could be compensated for by an equivalent amount of air capture.

Finally, air capture provides one of the few options to drive the carbon dioxide content of the air back down. In a sense, here you are capturing carbon dioxide that was released decades ago. This is the ultimate separation of sources and sinks not only in space but also in time. This ability to turn the clock back, at least partially, is important, because it is very difficult to envision a scenario in which the world manages to stabilize carbon dioxide concentration so that the total greenhouse gas impact is less than that of 450 ppm of carbon dioxide. Adding up all greenhouse gases, including for example methane, the world is only seven years away from breaching this limit.

Managing global carbon dioxide emissions is a huge task, but air capture could operate at the necessary scale. Right now the technology is still in its infancy, but one can already see an outline of how it may work in the future. A collector that can produce one ton of carbon dioxide per day would easily fit into a standard forty-four-foot shipping container. While the first few of these containers will likely cost $200K each, we expect the price to come down to that of a typical automobile or light truck.

For the sake of argument, let us assume that air capture units stay at this scale, and that they are mass produced like cars. With ten million such units operating, air capture would make a significant contribution to the world’s carbon balance. Ten million units would collect 3.6 billion tons annually or 12% of the world’s carbon dioxide emissions. If these units last ten years, annual production would need to be 1 million. This is a tiny fraction of the world’s annual production of cars and light trucks (approximately 70 million units). Thus, reaching relevant scales would certainly be feasible, although it would require a substantial commitment, and obviously a policy and regulatory framework that support such an effort.

Mineral Sequestration

Capturing carbon dioxide is just the first step in carbon management. After one has the carbon dioxide, it must be permanently stored to prevent it from returning to the atmosphere. Columbia University has an active research program on mineral sequestration, involving Juerg Matter, David Goldberg, Alissa Park and Peter Kelemen. Our group is also working on DOE-sponsored research on monitoring carbon dioxide in underground reservoirs.

Underground injection, or geological sequestration, is one option for carbon dioxide storage. It seems straightforward and simple, but it does not have an unlimited resource base, and it comes with the requirement of maintaining (virtually indefinitely) a seal to keep a gas that naturally wants to rise to the surface safely underground. By contrast, mineral sequestration has a much larger resource base, and it results in a stable, benign carbonate material that is common in nature and will last on a geological time scale. For all practical purposes, the storage of carbon dioxide in mineral carbonates is permanent. It requires energy to reverse the carbonation reaction. Therefore this reversal cannot happen spontaneously.

Mineral sequestration taps into a very large, natural material cycle on Earth. Volcanic processes push carbon dioxide into the atmosphere, and geological weathering removes it as carbonate. Carbon dioxide, which in water turns to carbonic acid, reacts with a base to form a salt. This happens every time it rains. There are plenty of minerals to neutralize carbonic acid, but this geological weathering process is very slow. Left to its own devices, nature will take on the order of a hundred thousand years to reabsorb and fixate the excess carbon that human activities have mobilized and injected into the atmosphere. The purpose of mineral sequestration in managing anthropogenic carbon is to accelerate these natural processes to the point that they can keep up with human carbon dioxide releases.

There are two fundamentally different approaches to mineral sequestration. The first is *ex situ* mineral sequestration.[5] Here one envisions a mine where suitable rock, usually serpentine and/or olivine is mined, crushed and ground up, and then in an industrial, above-ground processing plant, carbon dioxide is brought together with the minerals to form solid carbonates that can then be disposed of as mine tailings. Mining operations would be large, but no larger than current mining operations. It would take roughly six tons of rock to bind the carbon dioxide from one ton of coal. An above-ground mine producing coal in the Powder River Basin typically has to move ten tons of overburden in order to extract one ton of coal. Therefore, without wanting to minimize the scale of these operations, it is worth pointing out that current mining operations to produce coal already operate on the same scale.

The cost of *ex situ* mineral sequestration is directly related to the time it takes to convert base minerals to carbonates. In effect, the reactor has to hold an amount of minerals that is consumed during processing time. Thus, a reactor vessel which requires a day to complete the process is twenty-four times larger than a reactor vessel that finishes the job in an hour. Cost effective implementations must aim for a thirty to sixty minute processing time. There are very few minerals that are sufficiently reactive to achieve this goal. The only ones that exist in large quantities are serpentine and olivine. A recent study performed by the USGS and two of my students has shown that in United States, the resource base of these minerals is ample and could cope with US carbon dioxide emissions[6].

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[5] Lackner, K. S., C. H. Wendt, D. P. Butt, J. E.L. Joyce, and D. H. Sharp (1995), Carbon Dioxide Disposal in Carbonate Minerals, *Energy*, *20*(11), 1153-1170.
[6] For more information, see: http://pubs.usgs.gov/ds/414/.

Worldwide, these minerals are sufficiently abundant to cope with all the carbon dioxide that could be produced from the entire fossil fuel resource.

Somewhat surprisingly the cost of mining and managing the tailings is quite affordable; estimates are below $10 per ton of carbon dioxide.[7] The cost that still needs to be reduced is the cost of the neutralization or carbonation reaction. In nature the chemical processes are slow and accelerating them either costs energy (which is self-defeating as it leads to more carbon dioxide emissions) or money. Today, total costs are estimated around $100 per ton of carbon dioxide, which makes costs roughly five times higher than they would need to be for a competitive process. Overcoming a factor of five in costs sounds challenging, but most alternative forms of energy still have high costs or started out with costs that were even further away from what would be required in a competitive market.

The second approach to mineral sequestration is *in situ* mineral sequestration. In this case the carbon dioxide is injected underground just as it is in geological storage, but for *in situ* mineral sequestration, the site has been carefully selected so that the carbon dioxide will react with the local mineral rock and form carbonates underground. The result will be carbonates that form solids, or in some case remain dissolved in the pore water deep underground. For this to be useful, the reactions will have to bind all or most of the carbon dioxide on a time scale that is suitable for human decision making. If it takes more than a few decades for the carbon dioxide to bind, the carbonation process comes too late to affect human decision making. Nevertheless, a few decades is a lot longer than thirty to sixty minutes, which is the time limit for an above ground reactor used for *ex situ* mineralization. As a result, a larger variety of minerals are available for *in situ* mineral sequestration than for *ex situ* mineral sequestration. Of particular interest are basalt formations. At Columbia University we have tested this in our own backyard on the Palisades along the Hudson River. On a larger scale in the US North West, the Columbia River Basalts provide an inexhaustible resource base for *in situ* mineral sequestration. The Earth Institute is also involved in an *in situ* demonstration project in Iceland called the CarbFix project, as Iceland boasts some of the freshest and therefore most reactive basalt formations in the world.[8]

Mineral sequestration could play an important role in carbon management, if R&D could drive the cost down. First, mineral sequestration would provide a very different alternative for storing carbon dioxide that would provide a more permanent and potentially safer method than geological storage. The uncertainties in geological storage may well result in a general downgrading of the resource estimates, leaving only remote and particularly well characterized storage sites.[9] For example, underground storage of carbon dioxide in seismically active areas is almost certainly going to be challenged by nearby communities due to public safety concerns. Luckily, California has very large serpentine deposits and could entirely rely on mineral sequestration.

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[7] To set the scale, $10 per ton of CO_2 would add roughly 1 cent to the cost of the electricity from a 33% efficient coal fired power plant, it would add 8 cents to the gallon of gasoline.

[8] Matter, J. M. et al (2009), Permanent Carbon Dioxide Storage into Basalt: The CarbFix Pilot Project, Iceland, *Energy Procedia*, *1*(1), 3641-3646.

[9] Lackner, K. S., and S. Brennan (2009), Envisioning Carbon Capture and Storage: Expanded Possibilities Due to Air Capture, Leakage Insurance, and C-14 Monitoring, *Climate Change*, *96*(3), 357-378.

Second, particularly *ex situ* mineral sequestration may provide a virtually unlimited supply of carbon dioxide storage capacity and thus could act as an assurance that access to fossil fuels is not at risk. Mineral sequestration raises the value of the US coal reserves because it assures that they could be used if they are needed. Otherwise, the resource limitations on fossil fuels may not be the carbon in the ground, but the capacity of the atmosphere to accept the carbon dioxide. The world resource base in coal, tars, shales, and, potentially, in methane hydrates is so large that the accumulation of carbon dioxide in the atmosphere will need to be addressed.

Third, mineral sequestration makes accounting simple and it provides a high degree of assurance that the carbon storage is, for all practical purposes, permanent. The environmental footprint is contained to the site and to the time window in which the mine operates.

Combining Mineral Sequestration and Air Capture

It has been suggested that one could combine mineral sequestration and air capture into a single process. For example, one could use olivine or serpentine minerals as soil enhancers and rely on the soils to remove additional carbon dioxide from the air in a typical geological weathering reaction. Alternatively, it is possible to spread these minerals into the ocean, and let the reaction between the ocean and the carbon dioxide from the air happen spontaneously to neutralize the additional base.

I do not advocate such an approach, because I see major challenges with distributing that much material over large distances. For the same reason, I believe that in ex situ mineralization the serpentine has to be processed at the serpentine mine. There are several options: the coal plant could be collocated with the serpentine mine with the coal would shipped in; the carbon dioxide could be pipelined from a remote power plant to the serpentine mine; or the carbon dioxide could be captured from the air directly at the mine site. In no case, would the heavy serpentine rock have to move over large distances, because the shipment of large amounts of solid material is too expensive.

Furthermore, I see unnecessary environmental complications with distributing finely ground rock in the environment. Mineral rocks, when ground finely, represent environmental and health hazards, which are better dealt with in the confines of a mining operation rather than in open fields of enormous extended areas. Finally, these soil enhancers or ocean fertilizers will, by their very nature, change the ecological balance in the areas to which they are applied.

One of the major advantages of air capture and mineral sequestration is that both operations can be performed on a well contained and relatively small footprint. Thus, one can limit the environmental impacts to small areas and keep them well contained.

The Research Agenda

One of the major challenges facing mankind is to provide ample energy without destroying the environment. The energy sector is exceptional in that the problems we face cannot be solved by simply promulgating the state of the art worldwide. With state of the art technology in water and food the world would be assured plenty fresh water and plenty of food. However, the state art in energy is based on fossil fuels without carbon management, and its continued growth would wreak environmental l havoc. While there is reason to believe that technologies for carbon management can be developed, they have not been developed yet, and thus it is necessary to create a large and ambitious research agenda.

Stabilizing carbon and providing energy is a century scale problem. It is not just about retrofitting existing plants, but it is about developing a brand new energy infrastructure. The power plant of the future will be different from conventional plants of today. Success will require a portfolio from basic research to commercial applications. Learning by doing will not happen until we actually do build a new infrastructure.

Most of the immediate research agenda does not fit with the goals and aspirations of a company in the private sector. Since there is no market for carbon reduction in the absence of regulation, it is difficult to appeal to a profit motive. However, since there is no accepted technology to solve the problem, it is difficult to force new power plant designs through regulation. Thus, public R&D must make major contributions to solve the problem of carbon dioxide emission and demonstrate feasibility

There are very few resource pools for providing the amount of energy that the world will need in the second half of the twentieth century. The only sources big enough are solar energy, nuclear energy and fossil fuel energy combined with carbon capture and storage. In developing a sustainable energy platform, the world will need to place a big bet on all three options and hope that at least one of these bets pays off. In the unlikely event that all three resources fail to become sustainable and affordable energy resources, the world will be hit by an energy crisis of unprecedented proportions. Developing these alternatives will take a long time and the second half of the twentieth century is not that far away. The world has been working for more than fifty years on alternatives to fossil fuels – so far without success.

R&D will need to span the gamut from basic research to testing out new pilot plants, and from physics to health sciences. Nearly by necessity, research will span agencies from the National Science Foundation to the Department of Energy, from National Institute of Standards and Technology to the Environmental Protection Agency. Energy is important enough that it should be woven into nearly all aspects of technology development. Specific to air capture and mineral sequestration, research needs to focus on better sorbents, reaction kinetics, carbonate chemistry, and catalysts to speed up reactions. In applied research, we should consider applications in which carbonate disposal could become a byproduct of mineral extraction. We need to find better ways of producing carbonates from serpentines, and develop advanced capabilities of modeling the weathering of basalts in the presence of carbon dioxide. Demonstrations of the technology are necessary if they are ever to be introduced in the market. Altamont Pass was able to convince the world that wind energy has a future. Imagine what a large air capture park could do to convince the world that capturing carbon dioxide from the air is both possible and practical.