

THE CHALLENGE OF CO₂ STABILIZATION¹

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Stabilizing atmospheric greenhouse gas concentrations by mid-century is one of the world's great challenges; it will require a complex mix of technology, economics, and politics. In order to appreciate what might be done to move toward that goal, I review the energy landscape as important context to understanding the political and technical steps that might be taken.



Steven E. Koonin

THE GLOBAL ENERGY LANDSCAPE

The world's demand for energy today is characterized by a large, slowly growing per capita consumption among the one-sixth of the global population that lives in the developed world and by a small, rapidly growing per capita consumption in the developing world.

Plausible projections to mid-century (FIG. 1) show growth of future demand driven both by the economic improvement of one-third of humanity and by population growth, from the present 7 billion to an approximate maximum of about 9 billion. Energy demand is expected to increase by some 40% by 2030 and almost double by mid-century, with 75% of this increase coming from the developing world.

Now, and in a future projected from historical trends, the great majority of the world's primary energy comes from fossil fuels. Coal, oil, and gas provide almost 80% of today's primary energy. Even though the use of renewable energy sources is expected to grow strongly, by 2030 it will still account for only a very small fraction of the world's energy

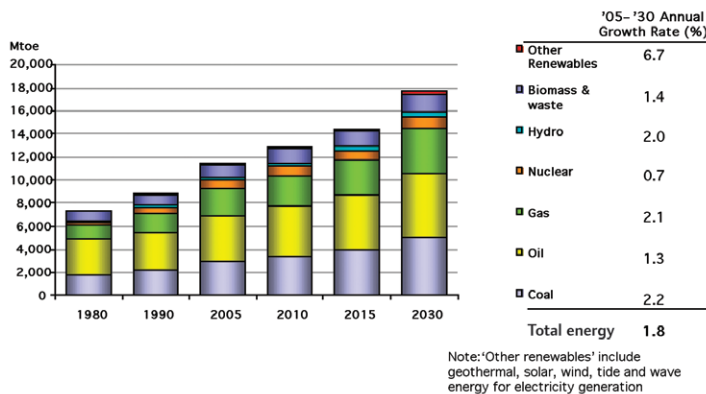


FIGURE 1 Global energy demand and supply through 2030. Mtoe = million tons of oil equivalent. SOURCE: IEA WORLD ENERGY OUTLOOK 2007 (REFERENCE CASE)

1 This paper contains material adapted from a Drell Lecture at Stanford University in January, 2008, and an Edison Lecture at the University of California at San Diego in July, 2008. A more complete presentation of some of the material can be found at <http://clients.mediaondemand.net/BP/>.

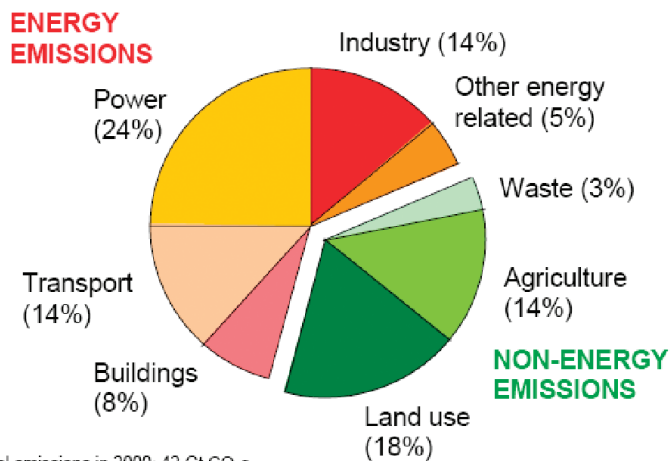
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production. Projections show that for the next many decades, most of our energy will still come from fossil fuels, because of their availability, low cost, and ease of use.

At current consumption rates, 40 years of conventional oil and 60 years of gas are known to be economically recoverable, with further, equal amounts of each that will likely be identified. And there is at least 150-years worth of coal, conceivably much more. Among these various fossil fuels, oil is particularly important for transport because of its high energy density; on the other hand, coal is used almost exclusively for electric power generation, and gas consumption is split among power production, industrial processes, and building-heat applications.

The much-discussed "peaking" of oil refers to reaching a maximum in the production of conventional crude. Whether or not that occurs in the next several decades, there is a variety of sources from which other liquid hydrocarbons can be produced; these range from tar sand oil and shale oil to coal-derived liquids and biofuels, which can significantly supplement conventional crude production. The extent to which these alternatives will be deployed will depend upon economics, technology, and security of supply.

The conventional use of fossil fuels adds greenhouse gases (GHGs), predominantly CO₂, to the atmosphere, as shown in FIGURE 2. Indeed, 60% of anthropogenic emissions arise from energy production, of which roughly 40% each come from power and heat and 20% from transport. Agriculture and deforestation make substantial non-energy contributions to the balance. The various GHGs have a range of atmospheric lifetimes; CO₂ has the longest, on the order of a thousand years.



Total emissions in 2000: 42 Gt CO₂e.
Energy emissions are mostly CO₂ (some non-CO₂ in industry and other energy related).
Non-energy emissions are CO₂ (land use) and non-CO₂ (agriculture and waste).

FIGURE 2 GHG emissions by source in 2000

Greenhouse gases have accumulated in the atmosphere to the point where they are very likely contributing to the climate change we are observing, and they will likely influence the climate even more strongly as they accumulate further in the coming decades. While the detailed impacts of future anthropogenic climate change are not known, we do know broadly that they will cause disruptions and entail costs that could range from merely inconvenient to catastrophic. The much-discussed increase in global temperature, whatever it turns out to be, is not particularly reflective of the possible consequences. These include increased desertification and precipitation, shifts in vegetation and fauna, sea level rise, severe storms, and so on. These are not things we'd want to happen.

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The cumulative nature of the GHG problem implies that drastic reductions in emissions are essential if we are to make a meaningful impact on concentrations. The usual societal response of dealing incompletely with a problem will only delay—not prevent—dangerous conditions. Emissions by the end of this century must be reduced by about a factor of two from their current value if we are to have any hope of stabilization. This requirement flies in the face of an anticipated doubling of energy demand by the middle of the century. So we must cut the carbon intensity of our energy system by a factor of four or so.

Complicating the situation is the heterogeneity of the emissions rates across the globe. As is the case for energy, per capita GHG emissions in the developed world (OECD nations) are large but growing relatively slowly, while those in the developing world were, until recently, much smaller, but are rising rapidly, as shown in FIGURE 3.

From this figure and related data, it is easy to see that: (1) emissions from the developing world now exceed those from the developed world; (2) with current trends, every 10% reduction that the developed world makes in its emissions (something it has not yet managed to do) is offset by less than four years of growth in the developing world; and (3) if the per capita emissions of either China or India were to grow to be equal to those of Japan (one of the least emitting of the developed countries), global emissions would increase by 40%. This contrasts sharply with the 50% decrease required by the end of this century for GHG stabilization.

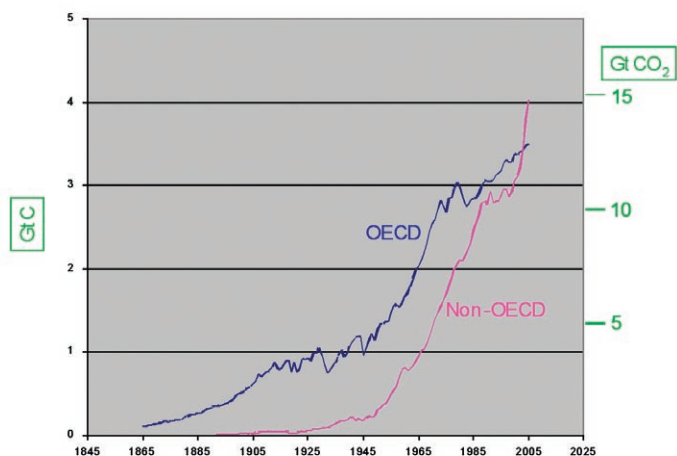


FIGURE 3 Annual CO₂ emissions from fossil fuels for OECD and non-OECD nations, 1865–2005. Source: Adrian Ross, October 6, 2008

MEASURES TO STABILIZE GHG CONCENTRATIONS

The picture painted by the factual discussion above suggests that it will not be a simple matter to stabilize atmospheric GHG concentrations. Three categories of measures could or should be taken to move toward that goal.

Promote Conservation

The most straightforward and cost-effective measure to reduce GHG emissions is conservation: the use of less energy. For example, about half of the world's energy is consumed in buildings for heat, light, and ventilation, and there are already many technologies that would enable this energy to be used more efficiently. Yet these technologies are not aggressively deployed, because of economic and social barriers.

Urban energy systems are another potential big win. Today, half of the world's people lives in big cities; by 2030, it will be 70%. Urban development with careful attention to building design, the integration of residential, commercial, and industrial spaces, and efficient transport systems for people, goods, and information could significantly reduce

energy use. However, greater efficiency does not guarantee conservation (for example, air conditioners that run with less energy would cost less to operate and thus lead to wider use). Higher prices and/or policies are needed to guarantee conservation, but these are politically difficult steps.

Decarbonize the Energy Supply

Assigning a serious cost to GHG emissions is an almost-essential policy measure, and this is now being implemented in some places around the world. Simple considerations show that in the developed world, a price of about \$50/t CO₂ would induce significant decarbonization (emissions reduction) of the energy supply, principally in power generation and heat. In transportation, reducing carbon emissions from mobile sources would require prices four to five times higher. This asymmetry is fortunate; stationary sources are responsible for 80% of energy-related emissions.

At a meaningful carbon price, the supply side of the heat and power sector would respond by increasing the proportions of gas power, onshore wind power, and nuclear power. Carbon capture and storage (CCS) will become increasingly attractive as a technology that can scale to a meaningful amount at reasonable cost. All of the above-ground elements of CCS have been demonstrated, but they have not yet been implemented on a commercial scale. The long-term integrity of below-ground containment is plausible, but also remains to be demonstrated. Monitoring criteria, liability, and public acceptance are all crucial issues to be worked on. The fully mature technology is expected to have costs comparable to those of nuclear power.

Several nations in the developed world are moving at various speeds toward pricing carbon, although it remains to be seen whether the price can be maintained at a high-enough level for a long-enough time to induce change. It is more difficult to imagine a meaningful price coming into effect in the developing world for many decades. Differing carbon prices around the world would surely impact trade patterns, industrialization, and outsourcing.

Adaptation and Geoengineering

Given the current energy landscape and its likely evolution, there is the possibility, if not the probability, that the world's best conservation and decarbonization efforts will not reduce emissions enough, and rapidly enough, to prevent concentrations rising above perceived dangerous thresholds. The obvious question "What then?" has seen little public discussion, perhaps for fear of distracting from the goal of mitigating emissions. Yet, given the realities, I believe it is irresponsible not to be considering this matter seriously.

Adaptation is already going on in parallel with mitigation efforts. Changes in infrastructure, agriculture, and behavior must be a major response to cope with a changing climate. Since adaptation can occur proportionally to the degree of climate change and since it is immediate in space and time, adaptation is likely to be the dominant response from society. There are reasons to believe that adaptation will be effective, given the extreme range of environments that humans already inhabit. However, it will be more difficult in the developing world, particularly in regions whose population lives at close to subsistence level (to say nothing about the risks to the biosphere).

And should the worst of the possible climate changes come to pass, geoengineering could emerge as the least bad of several bad choices. We are already intervening inadvertently in the climate system through GHG emissions. Other, more intentional, actions that one can imagine, such as removing GHG from the atmosphere through large-scale biosphere or thermochemical interventions or decreasing by a small amount the sunlight absorbed by the Earth, may offer a temporary, palliative response to a climate system gone awry. Apart from technical challenges, geoengineering presents difficult social issues, including questions such as "Who gets to decide?" or "What are the trigger points for intervention?" or "Who bears the liability for unintended consequences?" It is a route that future generations might very reluctantly consider as a last-ditch response to catastrophic climate change. ■

CO₂ CAPTURE AND STORAGE: POSSIBILITIES AND PERSPECTIVES

Wallace S. Broecker*, Professor, Columbia University

Few concerned with the need to stem the ongoing buildup of CO₂ in our atmosphere believe that this can be accomplished solely by some combination of conservation and non-fossil fuel energy sources. While both of these components are absolutely essential to any solution, even according to the most optimistic projections, they will fall short of the requirement to halt the CO₂ rise. Here, I present an objective description of solutions that have been proposed and end with my opinions, based on a long career of studying global chemical cycles.



Wallace S. Broecker at Hellisheidi, Iceland

The CO₂ rise must be halted, but the methods to accomplish this are still under debate. The facts are as follows. The growing demand for energy in developing countries certainly will far outstrip attempts at energy savings by the leading world powers. Coal will remain the cheapest source of energy for a very long time, and enough exists to fuel the planet for at least 150 years. The technology already exists to convert coal to gasoline at a cost less than what we now pay for petroleum. Thus, in the absence of some miracle that reduces the price of solar electricity or other renewable energy forms, additional options for halting the

CO₂ rise will be required. These options fit into a single category: CO₂ capture and storage (IPCC 2005). If we are to halt the rise in CO₂, we will have to implement technologies to capture it at its source in electrical power plants, and also to pull it back out of the atmosphere. And, of course, means for storing or disposing of this CO₂ will also have to be developed.

Evidence from studies of ice core and sediments demonstrates that since agriculture began ~8000 years ago, the climate has remained remarkably stable (Broecker 1997). This is in stark contrast to the preceding ~100,000 years, when there were very significant temperature fluctuations, from warm to glacial in just a few decades. Such rapid change suggests sensitivity to internal or external climate feedback. Also, the abrupt changes in paleotemperatures and atmospheric CO₂ concentrations (e.g. Petit et al. 1999) estimated from the ice and rock record may be telling us that the Earth's climate system has several distinct modes of operation and that it can jump from one mode to another in a matter of a decade or so. The only element of our climate system that has multiple modes of operation is the ocean's thermohaline circulation, which is sensitive to the fresh-water budget at high latitudes (Broecker 1997). This raises the question of whether the mode shifts revealed in the climate record were initiated by the oceans, and if so, what influence would there be from a rise in temperature driven by greenhouse gases (GHG). Increased polar ice melting from GHG-induced global warming could, in turn, influence thermohaline circulation. Rather than showing a linear evolution, the climate might follow a nonlinear path with sudden and dramatic surprises when GHG levels reach an as-yet-unknown trigger point.

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OVERVIEW OF POSSIBILITIES

Capture of CO₂ Emissions from Electrical Power Plants

Currently, roughly one-third of the CO₂ produced from fossil fuel burning in the USA is emitted from electric power plants. Retrofitting coal-fired plants currently in use for CO₂ capture is in many cases more expensive than replacing these plants with a new breed in which coal is treated with steam, thereby creating carbon monoxide and hydrogen (Rubin 2008 this issue). These gases would be oxidized in fuel cells, creating CO₂ and H₂O as end products. But this option currently does not cover the remaining two-thirds of American fossil fuel energy use. Hence, were there only the capture option, some means of extending its reach would have to be developed. For example, automobiles could be run on the hydrogen or the electricity generated by these plants, or gasoline and jet fuel could be manufactured by combining the hydrogen and carbon dioxide.

Capture of CO₂ Directly from the Atmosphere

Lackner et al. (1999) point out that despite the fact that air contains far less CO₂ than the gas emitted from an electric power plant, the cost of capture is dominated by the portion that represents release of the CO₂ from the capture medium. Thus, capture from air is as feasible as direct capture from a smoke stack. Lackner et al. (1999) also point out that a wind turbine moving at a reasonable wind velocity would only have to be two orders of magnitude larger than a collector that captures CO₂ to compensate for the emissions from a diesel engine that generates the same amount of electricity. Hence, just as wind turbines are competitive, so also should be air capture. The problem is that no one has yet demonstrated that CO₂ can be captured from air at an acceptable energy cost. To my knowledge, only one serious effort is underway to develop such a system. GRT, a company in Tucson, Arizona, USA, has been working on this problem for almost five years. They claim to have found the key and promise that by 2010 a commercial prototype will be available.

CO₂ Burial in Spent Petroleum Reservoirs

At best, only about half of the petroleum contained in oil fields comes out easily. As this resource becomes ever more scarce, hence more expensive, it will become financially favorable to implement what is known as improved (IOR), enhanced (EOR), or tertiary oil recovery (Lake 1989). In one method, CO₂ is pumped into the reservoir, where it entrains part of the remaining petroleum, decreasing the oil's viscosity. The CO₂ is carried back to the surface and is then separated from the petroleum and reinjected. In itself, this is not a storage solution, but because large quantities of CO₂ are needed and must be transported to the reservoir, future demand by oil companies could provide a jumpstart for the commercial implementation of CO₂ capture and transport. Also, when the enhanced recovery process has run its course, the spent reservoir can become a CO₂ storage depot. Oil-reservoir storage is discussed in detail by Benson and Cole (2008 this issue).

CO₂ Burial in Saline Aquifers

Large regions of every continent are underlain by sedimentary rocks. Below a depth of a kilometer or so, the pores in sedimentary rocks are generally filled with hypersaline water, which is of no value for agriculture. A strategy for CO₂ disposal is to drill into these aquifers and pump in liquid CO₂, displacing the resident water. The Norwegian company Statoil is already successfully disposing of CO₂ separated from natural gas in such an aquifer beneath the North Sea (Torp and Gale 2004).

CO₂ Disposal in the Deep Sea

The ultimate fate of the majority of fossil fuel CO₂ is dissolution in sea water. There, it is neutralized to HCO₃⁻ by reacting with carbonate and borate and with the CaCO₃-rich sediment that covers much of the deep sea floor. However, the deep sea is ventilated on a time scale of many centuries, so little of the excess CO₂ produced during this century would be neutralized in this way. However, an option to short-circuit

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the slow delivery pathways is to pump liquid CO₂ down into the deep sea. CO₂ delivered to depths exceeding 3.5 km is denser than seawater and would sink to even greater depths (IPCC 2005; Adams and Caldeira 2008 this issue). Further, it rapidly reacts with seawater to form an even more dense clathrate slush, which would accumulate on the ocean floor and then gradually dissolve and disperse.

CO₂ Disposal in Basalt

Layered basalt provinces, such as the Columbia River sequence in the USA, the Deccan Traps in India, the Siberian Basalts in Russia, and many more, offer not only storage depots for captured CO₂ but, more importantly, a means of low-temperature mineralization. Water charged with abundant CO₂ reacts with basalt, releasing Mg bound in pyroxene and olivine, which then combines with carbonate to form highly stable MgCO₃ (magnesite). Water with lower quantities of CO₂ reacts with plagioclase, releasing Ca which forms CaCO₃ (calcite). While these reactions have been carried out in the laboratory and are known to occur in nature, many questions still exist about their kinetics and by-products (McGrail et al. 2006; Matter et al. 2007; Oelkers et al. 2008 this issue). What fraction of the CO₂ injected into basalts can react before it finds its way back to the surface? Do the carbonate minerals so formed clog the plumbing? Will alteration by-products (silica, clay minerals, zeolite, etc.) coat the surfaces, slowing the reaction between the CO₂-charged water and the rock? Clearly, experiments must be conducted to answer these and other questions.

Disposal in Lakes Beneath Ice Caps

Although very likely unacceptable from an environmental perspective, disposal of CO₂ in lakes beneath the Antarctic ice cap is certainly a geochemically sound storage option. At the temperatures and pressures prevailing in that environment, CO₂ would form a clathrate that would settle to the rock floor beneath the lake. Unlike disposal in the deep sea, the clathrates would not dissolve because, in the closed system of the lake, the overlying water would quickly become saturated in CO₂ gas. Although the formation of clathrates (6H₂O-1CO₂) would remove CO₂ from the lake's water, the heat released during their formation would melt a nearly equivalent amount of ice from the lake's roof.

Mineralization of Magnesium-rich Rocks

In the long term, it might turn out that the best option is to mine ultramafic rock (i.e. rock made almost entirely of magnesium and silicon oxides), grind it in a processing plant, and react it with captured CO₂ to form MgCO₃ (magnesite) (Seifritz 1990; Lackner et al. 1995). The products would be stored in the pits created by the mining. The main obstacle is to find a means to do it economically in terms of both money and energy costs (IPCC 2005).

Seafloor Disposal

Going a step beyond storage in the deep sea, it has been proposed that CO₂ be injected into the basalts that line the mid-ocean ridge crest or in CaCO₃-rich sedimentary sequences (House et al. 2006; Levine et al. 2007).

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A FEW WORDS IN PERSPECTIVE

After this brief, objective summary of capture and storage options, I now add my own opinions. These are based on a long career, much of it spent studying global geochemical cycles.

With regard to capture, I strongly favor direct capture from the atmosphere. For a number of reasons, I consider it an absolutely essential component of any strategy designed to stem the buildup of CO₂:

1. Because facilities for such capture are not linked to the energy grid, they can be located anywhere on the planet.
2. As envisioned by Global Research Technologies, GRT, the company in Texas developing this technology, the individual units will be "Toyota"-sized (each capable of capturing one ton of CO₂ per day), as opposed to "battleship"-sized coal-gasification facilities. As a result, they could be mass produced and more easily distributed. As is the case of automobiles, the design could be continually upgraded, making them ever more durable, efficient, and economical.
3. Once the rise in CO₂ has been stemmed, air capture can be used to bring the CO₂ content of the atmosphere back to an acceptable level.
4. Because some sort of international agreement regarding the distribution of future CO₂ emission rights will eventually have to be negotiated, as a bargaining chip, the rich nations could offer to remove a portion of the CO₂ released during the preceding decades. In this way the playing field can be leveled.

With regard to disposal, I lean toward the deep ocean as the most favorable early-stage option. However, in response to the strong Greenpeace stand against what they refer to as ocean "point pollution," little is being done to explore either the costs or the environmental consequences of this option. Their stand includes a threat to disrupt any attempt to conduct pilot experiments, so in a sense, they hold a pocket veto. I consider this to be an extremely unfortunate circumstance, and I have initiated a campaign aimed at convincing them to abandon such aggressive tactics.

I am also convinced that, in the long term, we must turn to solutions that involve chemical neutralization (immobilization) of CO₂, as opposed to simply storing it in gaseous form. Hence, I consider petroleum reservoirs and saline aquifers as interim storage solutions. Ultimately, we must learn to economically bind CO₂ with the magnesium and calcium contained in silicate rocks, whether it be under in situ or ex situ conditions. As a participant in the basalt storage project currently underway in Iceland (Oelkers et al. 2008 this issue), I have become aware of the complexity of the required research.

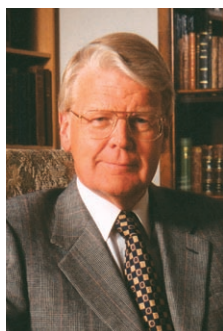
Looming in the wings is yet another technological fix designed to deal with the rise in greenhouse gases. It involves purposely altering our planet's albedo by delivering large quantities of SO₂ to the stratosphere (Wigley 2006). Once there, it would be oxidized to form H₂SO₄ aerosols. These aerosols would reflect sunlight away, thereby countering greenhouse warming. I do not consider this to be a solution, but rather an insurance policy against a bad CO₂ trip. As we have assumed the role of planetary stewards, we must strive to clean up our waste products, rather than treat them with Band-Aids!

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SOLVING THE BIGGEST PROBLEM

Ólafur Ragnar Grímsson, President of Iceland

Important decisions concerning the future direction of mankind must be based on the best available scientific knowledge. Real progress is achieved when we succeed in bringing together, for a common purpose, scientists and decision makers. In that spirit, I have supported cooperation between universities in Iceland, Europe and the United States aimed at sequestering carbon dioxide in basaltic rock, hoping that we can prove that it will stay there in solid form forever.



Ólafur Ragnar Grímsson, the President of Iceland

Over a decade ago, when I delivered as President my first New Year's Address to the people of Iceland, I emphasised the importance of dealing with the threat of climate change. I referred to the scientific work of Dr. Wallace C. Broecker, professor at Columbia University. At the time, I had never met him, but I was impressed by his research into the conveyor belt of the ocean currents and how it advanced our understanding of global climate.

When Wally Broecker and I subsequently met at the Global Roundtable on Climate Change, convened in New York at Columbia University, I discovered his interest in Iceland, and thus I decided to encourage cooperation among Wally,

his Columbia colleagues, Klaus Lackner and Juerg Matter, and outstanding Icelandic scientists.

It was both a pleasure and an honour to be able to invite Wally Broecker to Iceland to deliver the first Presidential Lecture, a new series which I initiated early in 2006. During his stay in Iceland, we decided to establish cooperation among the Icelandic scientific community, energy companies, environmental agencies and international experts to further Wally's idea of setting up a scientific consortium in Iceland which would conduct a pilot project on binding carbon in Icelandic basaltic rocks.

I believed that if we could succeed in getting such players interested in the project, it could lead to a major contribution from Iceland to the fight against climate change.

The Icelandic people have for centuries been proud of Iceland Spar, the mineral that shines like silver; in our language it is called "silver-rock". We know that it is formed through the interaction of carbon, oxygen and basalt. Thus it is exciting for us to find out whether this compound can be created in a special way; whether carbon dioxide can be bound chemically into a solid form underneath the beautiful Icelandic landscape instead of being released into the atmosphere.

We succeeded in establishing a fully fledged scientific project involving world-class scientists, professors, doctoral students and energy-company experts. They were all enthusiastic. It has been a great pleasure for me to work with Sigurður Reynir Gíslason and other professors at the



The CarbFix CO₂ injection site in southwest Iceland. The Hellisheidi power plant under construction is in the lower right, the moss-covered basaltic lava flow in the center of the figure, and the basaltic hyaloclastite (broken glass) mountains in the distance. The injection well is located in the lava fields in the upper left part of the photo. PHOTO: S. R. GÍSLASON



Helgi Arnar Alfreðsson, one of several PhD students in the CarbFix project, sampling one of the monitoring wells at the Hellisheidi site. PHOTO: E. S. EIRKSDÓTTIR

University of Iceland, the experts at Reykjavík Energy and foreign scientists, such as Eric Oelkers, who has been firmly behind the project from the very beginning.

It is still too early to predict a breakthrough from this intriguing project, but when international journalists or world leaders want to know more, my answer has always been: these outstanding scientists and experts would not be spending their valuable time on this effort if there was not at least a reasonable probability of success. When we know the results, and if they are positive, we will be able to engage in discussions with government leaders, scientific institutions, universities and other organisations in Russia, India, the United States and other countries where there are huge expanses of basaltic rock.

I welcome the opportunity to share these reflections with your readers and thus encourage scientists to work hand in hand with policy-makers in order to solve the biggest problem facing mankind at the dawn of the 21st century. ■

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