

**Energy Future Coalition Steering Committee Meeting Notes
May 12, 2015**

Steering Committee

Tom Daschle, The Daschle Group
Greg Dotson, Center for American Progress
Dan Esty, Yale University (by phone)
Vic Fazio, Akin Gump
Mike Finley, Turner Foundation
Thea Lea, AFL-CIO
Thomas Lovejoy, United Nations Foundation
Mark Safty, University of Colorado Denver
Steve Symms, Partner, Parry, Romani, DeConcini & Symms
Timothy Wirth, United Nations Foundation

Guests

Andrew Deutz, The Nature Conservancy
Ed Dunlea, National Academy of Sciences
Brenda Ekwurzel, Union of Concerned Scientists
Mohamed El-Ashry, United Nations Foundation
Shelley Fidler, Van Ness Feldman
David Goldston, Natural Resources Defense Council
Kalee Kreider, United Nations Foundation
Bob Perciasepe, Center for Climate and Energy Solutions
Rafe Pomerance, Polar Research Board
Ernie Shea, 25x'25
Hank Terhune, Akin Gump
Dave Titley, Penn State University
Janie Wise, Cassidy & Associates

Climate Intervention: The National Academy Reports

DAVE TITLEY

I'm going to give an overview of the report and explain why we call it climate intervention and not geoengineering like everyone else. Why do we have two reports, when we were really only asked to do one? And then Jen Wilcox, who is one of the world's foremost authorities on carbon dioxide removal and sequestration, will talk in detail about the carbon dioxide parts. I'll do the overview, a little bit on albedo modification – you may know it as solar radiation management – and then we'll turn it over to Jen.

I would be remiss not to mention Dr. Marcia McNutt, who I'd guess just about everyone here knows. Marcia was our chairperson, and it was through her leadership and skill that we took something, which was a very contentious project, and got us to consensus, so I would be remiss not to thank her publicly for that service.

As I said, we have two reports, the reason being that most people call this geoengineering, and it's kind of a mishmash of different techniques, all the way from painting roofs white to some sort of science

fiction thing of thousands of aircrafts spraying stuff into the stratosphere, and everything in between. As we talked to people, we realized this term had very different meanings to different folks. What we are trying to do on the committee is to accurately, and without prejudice, describe what these techniques are. We're not intervening in the Earth *per se*, we're intervening in the climate.

Intervention, by definition, is an intentional action to make something better, and that's at least the purpose. Now, we've all probably watched too much reality TV in the last 15 years, and we know that interventions sometimes have unexpected and not always great side effects. We think climate intervention is a more accurate and non-prejudicial, neither good nor bad, way of simply describing what it is we're trying to do.

Basically, when you're taking out the carbon dioxide, by and large the risks are much better understood and much lower, but you have huge scale issues, and Jen is going to talk about those issues. When you're reflecting sunlight, it's almost the flip side of that coin. The risks are significant and unknown, but we can do this at scale, and we know we can do this at scale because volcanoes do this at scale. Relative to the cost of adapting, I mean you can argue about numbers, but it's sort of something you can do. The issue with carbon dioxide removal is, can you do it at scale and at an affordable cost? That's why we split this up, because they really are very different techniques.

I probably don't need to spend much time on this first slide with this group – anybody here not sure that the climate is changing? The evidence, as the IPCC assessment and I think the vast majority of climate scientist show, is pretty overwhelming. We know the climate is changing, and I think the second bullet is just about as obvious – since we have implicitly built our civilization on climate stability, the fact that we are no longer in a stable climate impacts everything. It impacts us, the ecosystems, and of course, the economy.

I imagine many of you are quite familiar with how the National Research Council and the Academies work. I think it's important to note that the National Academies itself, Dr. Cicerone himself, basically put his internal funds into supporting this project. Dr. Marcia McNutt was the chair. It was done as a very typical NRC committee, so we write the report, and then it is reviewed by another committee of distinguished colleagues. There were a lot of processes put in here to ensure, to the best of our human abilities, that we had a quality product.

I'm going to spend a little bit of time on Recommendation One. I would say this is our most important recommendation, in my personal opinion. The committee didn't rank them, but there's no silver bullet to getting us out of the climate challenge. So our recommendation is that we should continue to focus most on reducing greenhouse gas emissions and then adapting to the changes that we already have, because we know how to do it. Technically we know how to do it, politically we all understand the issue, we understand the risks, and the ways to do this are at a much greater state of technical readiness than any of the other climate interventions.

I'm going to talk about albedo modification. What do you do to simulate a volcano? You put aerosols up into the stratosphere, 50, 60, 70 thousand feet up into the atmosphere. The other thing you can do, at much lower levels – like a few thousand feet – is brighten the tops of the clouds off the west coast of continents. We call this albedo modification and not solar radiation management. We simply do not know enough to manage the sun's radiation. So what are we doing? We're reflecting sunlight, but to think we've got this nice, fine-tuned dial that we can set and everything's going to be just fine is frankly

the height of hubris. This is why we use the term albedo modification rather than solar radiation management.

This slide shows some of the risks that albedo modification poses. It messes about with the ozone and the stratosphere. Many modeling studies, as well as observations from nature volcanoes, show that it changes how precipitation falls – so does it mess with the monsoons in south Asia? The rainfall in the Amazon, even if you're doing things half a world away? The more you try to understand the regional variability, the less certainty we have in that; different models give you different answers.

We talk about this millennial dependence, and what we mean by that is: Let's say we start doing albedo modification, and within a band you do control the temperature. If you do not concurrently come down on your greenhouse gas emissions, your CO₂ or CO₂ equivalent keeps going up. And if you do that, you're going to have to do more and more albedo modification and buy the millennial dependence, because it takes so many thousands of years to get CO₂ out of the atmosphere naturally. You're now committing yourself to doing something longer than virtually any other institution in the world. All the models show that if you stop for whatever reason, you will rapidly come up to the climate you would have had within a year or two. Then there are the social and legal issues of who sets the thermostat. So, Recommendation Three is: Do not deploy albedo modification.

Recommendation Four says that we should do research. We realize there are a number of scenarios that are distasteful. As risky as this would be, there are a couple of scenarios that could happen. Let's say you have a climate emergency, this could be crop failure extending from California through the Midwest, the South Asian monsoon failing for three years in a row, or Atlanta running out of water. We could sit here and come up with many climate emergencies, and it could easily not be in the United States. Does there then become intense political pressure for our leadership to do something? Many of us have been in these positions in the government and can understand that there's a pressure; citizens want to see their governments doing something. If you don't understand the risks, then those options might look really attractive, not because they're low-risk, but because we haven't quantified those risks. They could look pretty good because you could see a lot of pain and suffering going on right now.

Another scenario is: We get serious about reducing our greenhouse gases, but by the time we do that, the science is pretty sure we're going to bust through this two-degree Celsius overall temperature increase. You could see that the world might make the decision to say, "No, we will reduce our greenhouse gases, and through carbon dioxide removal we will get ourselves down to the point where, naturally, we can sustain two degrees or less." That would be maybe 100 years or so.

The third scenario is that the United States is not the only country with a vote. Another country or even a non-state actor might say, "I don't like the climate in my part of the world, and I'm going to do something about it because you guys haven't done anything." So the President calls up her science advisor and says, "So, what should I tell these people? Should we ignore it? Should we say, okay, fine, and join them? Or should we say, unless you cease and desist within 72 hours, the full weight and power of the United States will come down on you?" What would the advice be to the President, to our most senior leadership, if that happened? If you don't know the risks, if you haven't done the science before that, it gets really hard to answer those questions. So that's why we're recommending the R&D. Much of the R&D we think should be done first actually benefits our understanding of the basic climate system anyway. It turns out that our understanding of aerosols is not all that great, and that's a huge part of understanding the albedo modification. Just understanding aerosols better would actually help us a lot.

Our ability to monitor the climate long term is not very good, and it may not be getting better. The committee recommends that we do need to be able to better monitor our climate – the long-term time series are very important, and staggering from system to system is not really the best way to do that.

Intervention in the Earth's climate needs to be informed by far more than just scientists. These are political, societal, legal, and ethical decisions. The scientist should be at the table and should have a voice, but it's just *a* voice, not *the* voice. Jen is going to go down the attributes of carbon dioxide removal, and you'll see that it's almost the opposite side of the coin as what I've talked about with albedo modification.

REID DETCHON

Rafe, you've been an advocate for additional research, do you want to say something?

RAFE POMERANCE

Thank you, Reid. The report is a great success; they got it just about right in terms of substance and the timing and the political context, which is very tricky. I think it has moved the ball forward in terms of moving toward what we need to do, which is a research program. To offer a couple of thoughts, I actually think the climate system is further along than the Academy in this particular report. I think the situation is more serious and will drive this question quicker than we know. Here's one example – the United States has taken on the chairmanship of the Arctic Council at a historical moment. The Arctic is unraveling; the systems we know there are coming apart with grave consequences for the Arctic, the lower 48, and the rest of the world.

One example, which is quite recent, is that we now know the permafrost contains more than double the carbon content of the atmosphere, stored over thousands of years without being emitted and becoming carbon dioxide. We have estimates of the annual emissions as the permafrost thaws – it's now thawing. The scientific community is forecasting global annual emissions – they are substantial, and they will continue for a very long time. I think the average annual emissions in the 21st century will be about 10% on annual of global emissions, it's like introducing a new United States into the system. Can we let this continue? And what's the scenario, given continued global emissions increases? What happens to concentrations and temperature, because the emissions of carbon from permafrost are temperature-dependent? Will society let this continue?

Sea ice is disappearing, Greenland is shrinking, snow cover is diminishing – all this adds up to a level of urgency that hasn't quite developed in the politics of this. I think, in one other Academy report on future research needs in the Arctic, they suggested the actual geoengineering question would come out of the Arctic; that there would be pressure for greater research and understanding coming out of the deterioration of the Arctic. I think the urgency is upon us, and we will see it more as time goes on.

The challenge for the Executive Branch is, how does it respond to the key recommendation, which is to have a research program? We have no organized research program, probably in large part because of the politics. When John Holdren raised this issue early on in the first Administration, he got burned up. He finished an interview on the subject, and he got so burned because of the political correctness problem that he hasn't touched it since, with good reason.

TIM WIRTH

What was it again, there should be a specific Arctic research program?

RAFE POMERANCE

They asked Holdren if we should we have a geoengineering research program, and he said, “Of course.” That was a political problem. I think the way forward is for the Executive Branch to respond to the Academy report and say, “What are we going to do?”, and they have to come up with a way to do that in the context of Paris. We’re not going to launch a big effort before Paris; we can’t, because any big, explicit effort of research, even if we agree to do it, is too risky as a political matter going into a global negotiation like that.

TIM WIRTH

Is it that risky if it’s targeted on the Arctic?

RAFE POMERANCE

Yes, for the United States it is too risky for political reasons. We will be attacked for trying to get out of other responsibilities.

TIM WIRTH

The assumption would be, if we were to do this for the Arctic, it’s because we want to avoid tough choices?

RAFE POMERANCE

Right or wrong, that’s the fear. So I don’t know if you’ll see anything before Paris, I don’t know if you’ll see anything after.

TIM WIRTH

What has the IPCC said? Have you taken it out of the United States framework?

RAFE POMERANCE

If it came out of a multilateral framework like that, it would be a lot easier. One other challenge here is that we do face this issue in many multilaterals, it comes up – the Convention on Biological Diversity, World Meteorological Organization, IPCC, etc. We have enough of a policy to say ‘don’t take the option off the table’, but that’s about it.

STEVE SYMMS

Can you briefly comment on what’s happening in the Antarctic?

RAFE POMERANCE

I’ll turn to Brenda, do you want to comment on the Antarctic?

BRENDA EKWURZEL

The Arctic is showing the most rapid change. There are parts of the Antarctic, like that part that sticks up towards South America, showing very rapid change, and we’re seeing some of the outlet glaciers where the sea ice just pulses back and forth seasonally, and it’s pretty much a natural cycle. The stratospheric ozone and other aspects do play a big role in Antarctica, but it’s a big ice sheet that has a lot of stored ice for sea-level rise.

RAFE POMERANCE

The Academy chose not to define this as a so called ‘climate emergency’. That’s an interesting issue – what is it then? Are we in it?

DAVE TITLEY

We could spend a whole year coming up with scenarios on climate emergencies. My feeling is we could spend a whole year on that and then not pick the one that becomes a climate emergency.

RAFE POMERANCE

Someone has to define it, though. The ice sheets in Greenland have 20 feet of sea level rise and are shrinking – if the ice sheets are shrinking, is that an emergency? Would climate intervention do anything about it? We don't know. Florida is faced with inundation. The estimate is that sea-level rise will go up by three feet by the end of the century. Florida state is at stake, in a way – is that an emergency? What effect would an intervention have on sea-level rise? It would clearly affect the thermal expansion on the oceans, which is a major source, and it would affect the ice sheets and mountain glaciers. That's another way you might come at this.

MIKE FINLEY

We do a lot of work in Atlanta – we've seen parking lots covered with solar, we've seen reflective paint on asphalt parking lots. Has anyone done any analysis, to scale, to see what we could do just by reflective technologies on our asphalt parking lots and white roofs?

DAVE TITLEY

The white roofs are all good, there's nothing wrong with them, but they will never get to the scale we need. It's being looked at – we have the references in the albedo modification report. We kind of rolled up a number of different types of ways to reflect sunlight that are talked about. Locally, it could probably help with the heat island effect, but that's really more of a weather issue – it's not going to change the global climate, but that doesn't mean we shouldn't do it.

KALEE KREIDER

I wanted to address Tim's question about the IPCC. The IPCC has addressed geoengineering since its First Assessment Report in 1990. It began with looking at wide-scale reforestation all the way through to the most recent assessment, which included a couple of paragraphs in the Summary for Policy Makers, as well as the underlying report. It's probably too extensive to go into it, but they looked at different terminology – both sides of the equation here. They've also had a special meeting on geoengineering, and I think if you were to poll the IPCC right now, they would support more research and, in fact, have said clearly that research is pretty poor in this area.

If you look in the aerosols section of Working Group I, they also indicate that our knowledge of the underlying system as it relates to aerosols is really quite poor. On the research piece that Rafe mentioned, we're battling for research funding now on everything from medical research to climate change. I worked since 2000 to try and get a satellite launched, which we finally got off the ground, but for those of you who have worked on satellite funding, it's a grave and dire problem. It's not just Paris that's driving that we're not getting research in geoengineering, it's the fact that the U.S. Congress doesn't want to fund research. I think it would be a mistake for us to think it's just a climate problem; it's a congressional funding for scientific and medical research problem.

DAVE TITLEY

On the Arctic, it's certainly very serious. It's becoming more and more serious politically and in terms of climate change – think of all the stuff we did in the Cold War and add a rapidly changing climate and many more non-state actors.

TIM WIRTH

Who do you mean by non-state actors?

DAVE TITLEY

You have tourism, shipping companies, Shell, the Norwegians, the Russian oil exploration guys – you have a lot of big people up there, in addition to the five countries that have actual territories in the Arctic. From a technical perspective, when we looked at, “Well do you have to just make the Arctic colder?” you have some very counterintuitive results from albedo modification. You think you’re going to cool down everything, and sometimes you actually get a warmer Arctic. Now you can find other model runs that say different things. The answer is, we don’t know how to do that. Rafe is right, it’s not just the Arctic melting, but the Antarctic ice sheets are now showing increasing signs that they’re starting to melt, too. It’s because you’re getting relatively warm water at the bottom of these things, which lubricates them and moves them into the water. Those are going to be the issues, but I wouldn’t want to underestimate the complexity and the fact that we could very well be surprised.

Carbon Capture, Use, and Storage**JEN WILCOX**

This first slide goes over carbon dioxide removal strategies. Looking at some of these first ones, an example is changes in land use management – so reforestation of land, afforestation, and various agriculture practices. One example is low tillage of soil to prevent the carbon from being released into the atmosphere. At first we had a list that included biochar, and we felt that biochar didn’t fit into this category. There’s a lot of hype surrounding biochar, but the point is, if you’re starting with biomass and you’re making biochar from it, if you use the biomass correctly as fuel and you’re displacing a fossil fuel, then the net greenhouse gas emissions are actually lower when you use the biomass directly, versus the greenhouse gas avoided by using the stored carbon using biochar in the soil. So we have a very detailed description in the report, but we’re purposely not including biochar, to make that statement clear.

In addition to land use management, we have accelerated weathering, which embodies a few different approaches. Accelerated weathering can be thought of as changing the alkalinity of the ocean so that the ocean can uptake more CO₂. Another concept you may have heard about is looking at rocks in the Earth’s crust, called ultramafic rocks. They will readily produce carbonate, but the issue is that these rocks have to be mined. Some of these rocks are at the surface, and they will readily form carbonate, but that surface area isn’t great enough to impact climate on a significant scale. What you would have to do is inject the CO₂ into that rock, but it’s not exactly a porous material. So people are thinking about fracturing that rock and looking at trying to enhance the CO₂ uptake in the surface area to get more CO₂ reactivity, or something called ex-situ mineralization, which means you would actually mine the rock. You’d have to grind it to increase the surface area and reactivity of the rock and then form carbonate with that. My group has done some life-cycle assessments; if anybody’s interested, I can get you the papers. Essentially what we looked at is: Imagine if you do mine those rocks and grind them and react them with CO₂ – once you form the CO₂ aggregate, bound to the rocks, what do you do with it? What are the available markets you could use for that?

We looked at sand and gravel, we looked at the construction industry – those markets are very large, but they aren’t large compared to the global emissions of CO₂. So the markets would be on the order of sequestering millions of tons of CO₂, but we’re on the order of tens of gigatons of CO₂. At best, you’re looking at less than 5% of global emissions if you were to totally displace the sand and gravel industry

with these synthetic rocks. In terms of cost, it turns out if you really are mining the ultramafic rocks and transporting them and reacting them with CO₂, we're looking at about \$1,000 for every ton of CO₂ sequestered in those rocks.

Cement kiln dust is another possibility. From iron ore manufacturing you have particulate matter that can be used to react with CO₂. We also looked at all of these free particulate matter sources from industry that we could use to react with CO₂. That, combined with the other approach I mentioned, is still on the order of tens of millions of tons, so it's very small compared to the emissions – it's essentially accelerated weathering. You can think of them as oceans versus land, and that's how we've separated them in the report as well.

The next one is ocean iron fertilization. It's one we don't discuss in great detail, but it's the carbon dioxide removal strategy that has the highest risk associated with it. This is essentially looking at the natural pump in the ocean with algae and their uptake of CO₂, and if we were to put iron in the ocean to enhance the production of that algae, then we could enhance the CO₂ uptake. We know that there are also a lot of risks associated with that and increasing the algae production in the ocean, and what that might do in terms of oxygen reduction in the ocean for fish and all kinds of ecosystem issues. We didn't spend a lot of time on it in the report, given the potential high risks associated with that strategy.

The next two approaches, direct air capture and bioenergy, are different than the other ones I talked about. In the other ones, the carbon capture and sequestration are coupled, so in those strategies we're taking it out of the atmosphere, you're reacting it or you're storing it. You're doing that in air capture – you're separating the CO₂ out of the atmosphere, but then you have to do something with the CO₂. You can either use it, or you can store it. If you're looking at removing CO₂ permanently, it has to be coupled with sequestration.

Direct air capture is very different than capturing CO₂ from a power plant. If you have a coal-fired power plant, carbon dioxide has a concentration of anywhere from 12 to 15%. If you have a natural gas-fired power plant, the concentration of CO₂ in the exhaust is between 4 and 6%. Those are still dilute mixtures. They're gas mixtures of CO₂ and nitrogen and water vapor, and so in the separation process you have to pull CO₂ out of the gas mixtures, and CO₂ is fairly dilute in those systems. Direct air capture means that CO₂ has been emitted in the atmosphere and is extremely dilute – we're at 400 ppm today of CO₂ in the atmosphere. So that means we're having to separate CO₂ from an extremely dilute mixture, and the other issue with this is that, not only is it very dilute, but what is the energy source you're going to use to actually do the work associated with the separation?

If you have a coal-fired power plant, the energy comes from that power plant. They could take, say, a 20% hit, so instead of producing 470 megawatts at a 500 megawatt plant, maybe it only produces 380 megawatts because of the requirement of the energy for the carbon capture and separation. So if you have direct air capture, what do you need? You need a power plant to make this happen – and where are you going to get the energy for the power plant? It turns out if you use a coal-fired power plant to take CO₂ out of the atmosphere, you actually generate more CO₂ than you end up separating or storing. If you use natural gas, you break even. So this concept only makes sense if you're going to use a non-carbonized energy resource, like wind, solar, or nuclear.

The next part is bioenergy with carbon capture and sequestration. We're doing this today to a certain extent. There's a lot of power plants in the United States that co-fire with biomass, like switchgrass. So

instead of firing completely with coal or natural gas, can we use biomass? Imagine you have biomass that's taking up CO₂, and then you take the biomass, dry it, transport it, and burn it, but then you replant it. In an ideal world this is a neutral CO₂ source, but of course there's energy associated with drying and transporting it, so it's really not a neutral process. However, it could be a net negative CO₂ process: it could be that you have your bioenergy facility, you do your CO₂ separation, and then that CO₂ could be used for something or transported for storage. I think it's important to mention that these are two concepts: the separation process is one part, then what you do with this CO₂ stream is another question.

I'll just talk briefly about utilization. With utilization, what are the different options that we have? The number one CO₂ use is enhanced oil recovery. If you have CO₂ in a supercritical state, and you inject it into a reservoir, and it's mixable with the oil, then it changes the fluid properties of the oil – the viscosity, the density – and it makes that oil easier to recover. So you have oil sites that still have oil left in them that you can't recover using conventional strategies, but if you use supercritical CO₂, then you're able to get more oil out. Enhanced oil recovery is really the top strategy associated with the usage of CO₂, but it turns out that it's really just usage, not sequestered in these reservoirs.

For instance, because it costs something to make CO₂, if it's something from an anthropogenic source, what will happen is the oil will be recovered at the surface, and then they'll do a separation process to recover the CO₂. Then they'll use it again, pump it down to the subsurface and recover more oil, and they'll continue the process. From the references that I've read, anywhere from 15 to 20% of the CO₂ might be left behind, but for the most part they want to recover that CO₂ and reuse it. Of course, in this strategy, you're recovering oil and burning it to create more CO₂, but that is the number one market for CO₂ today. Most of the enhanced oil recovery of CO₂ is actually naturally sourced, and a small part is from anthropogenic sources, but I think that's becoming more and more common as this demand exists. At best, using state of the art technology, we're looking at something on the order of 100 million tons in total, so it's actually pretty significant. However, that's the total market, and that's in the U.S. The other uses could include the food and beverage industry, but again, in that case you're going to be re-emitting CO₂ back into the atmosphere.

KALEE KREIDER

We had a lot of proposals and new company startups working on replacing water use for fracking with CO₂ recovery. Did you all look at that – oil and gas recovery, fracking, and replacement of water – and look at the overall implications of that or just the CO₂ piece?

JEN WILCOX

Just the CO₂ piece. In terms of what we might be able to learn from fracking with water, a lot of the concern associated with CO₂ for enhanced oil recovery or CO₂ sequestration is the risk associated with inducing seismic events. A lot of the work that's been done on water is work that we can learn from, and so we talked about it from that perspective, in terms of experience associated with hydro-fracking, not associated with the displacement of water and what environmental impact that might have.

In terms of utilization, the food and beverage market is quite small. Why can't we make chemicals out of CO₂? We do, but if we look at the top 10 chemicals produced globally, the chemical industry is a fraction of the CO₂ we emit globally, about 1 percent. So these emissions are on a scale that we've never seen before. The only market that scales with it is the fuel market, so if you can make fuels from CO₂, that's very interesting, and there are plenty of groups working on this. The problem is that you're going to burn that fuel, so at best it will be a neutral strategy and not a permanent removal of CO₂.

The last aspect of this is the storage piece. What we considered in the report was looking at saline aquifers, depleted gas reservoirs, and CO₂ sequestration in methane-depleted coal beds. It's well known that there's enough pore space to store all the CO₂ we generate for a number of years to come. The question is, and this is why we advocate for research, how fast can we create those projects, and how reliable is the storage once it's injected? What's the likelihood of leakage, and what are the risks associated with it?

The next slide is on the recommendations. The committee recommends research and development investment to improve methods of CDR and disposal at scales that matter. And in particular, to minimize energy and materials consumption, identify and quantify the risks, decrease the costs, and develop reliable sequestration and monitoring.

This is a table that we created to give an idea of the scales of each method, in terms of an annual basis and cumulative, up to 2100, and the average costs associated with each. This allows us to break apart all these techniques and think about what kind of impact they might have. Then we can also remember that one ppm of CO₂ in the atmosphere is equivalent to about 18 gigatons of carbon dioxide.

On the next slide we look at land management, afforestation, and reforestation. At best, the annual rates look at a maximum of five gigatons of CO₂ per year, maybe 100 over the next 85 years, at a reasonable cost. If we look at accelerated weathering, again along the same scales, but in terms of the land, it is possibly more expensive. And with ocean iron fertilization, again, there are significant risks associated with that.

Bioenergy, capture, and direct air capture might have a significantly higher impact, but they may also be expensive. Some of the limitations with bioenergy are, for example, if we're looking at the population increasing to 9 or 9.5 billion, then we might have to think about competition of land area for food, so energy crops versus food crops. In terms of direct air capture, if you're using a non-carbonized energy resource, for instance solar, how much land area will be available? That might dictate how many of these direct air capture plants you could build.

This last slide is sequestration. In terms of the geologic sequestration numbers, some of the reviewers argued about this a little, saying that there's plenty of pore space for all of the CO₂ emissions to take care of us for hundreds of years. The question is, what's the scalability of the CO₂ sequestration approach? For instance, when you think of technology associated with the nth plan and something getting cheaper, today we have a very small number of monitoring activities set up. There are less than 10 active projects in which CO₂ is being separated and stored and having that stored CO₂ monitored. And they're all on the order of a million tons per year. According to the International Energy Agency Roadmap, we have to increase that by about 1,000 in order to make an impact on climate. If you're going to multiply those efforts by 1,000, how fast can we scale up safely? We would have to know that all of the sites in which we're sequestering CO₂ are reliable and safe. The cap or limits that we've posed on here are associated with the 2 degrees Celsius scenario.

On the next slide, we're looking at the research opportunities for CDR:

- Assess and improve strategies for performing and monitoring geologic sequestration.
- Explore strategies that increase the ocean's ability to store carbon without causing adverse effects.

- Continue research on combining biomass energy with carbon dioxide capture and sequestration, including exploration of approaches that do not form and sequester concentrated CO₂.
- Solicit, foster, and develop approaches for scrubbing carbon dioxide from the atmosphere that hold the potential to bring costs and energetics into a potentially feasible range.
- Land use management techniques that promote carbon sequestration.
- Accelerated weathering as a CO₂ removal/sequestration approach that would allow conversion to stable, storable, or useful carbonates and bicarbonates.

There's no silver bullet – we think it will be a portfolio of solutions, and it will take all of these little pieces to add up to something significant.

MARK SAFTY

Did any of the work that you conducted look at the question of associated water consequences of afforestation and reforestation on a large scale? If not, is there science out there that makes any useful projections about water implications?

JEN WILCOX

We did discuss water. In the report there are details of the data with water and detailed references of where that comes from. We did talk about ammonia in fertilizer because you emit CO₂ in the atmosphere in that process.

TIM WIRTH

Can you comment on carbon capture and sequestration in the traditional fashion of coal-fired power plants? We've been hearing about this for 20 years. A number of very large research facilities were built, and most of them have been shut down. We continue to hear that this is going to be a holy grail of some kind. It reminds me a little bit of what Rafe was saying about doing research on various other kinds of interventions; people are critical of that because it says you're going to avoid doing the hard work of mitigation. My guess is that carbon capture and sequestration has some of that to it – we don't have to worry about continuing to burn coal or continuing to develop traditional power plants, because we're going to get to carbon capture; and second, it's going to be so horrendously expensive that any kind of cost calculation becomes so significant; and third, by the time you get on a time curve for all this, you're well down the road past 2 degrees before you get anything big enough. That's a skeptic's view on carbon capture – what's your response to that?

JEN WILCOX

I agree. The state of the art technology today is amine scrubbing. You've got \$100/ton, that's what the industry says, but there are others who say it is closer to \$60/ton. The reason why that's the state of the art technology is because we've been doing it for a long time – the patent was filed back in 1930 or 1940, and it was for the food and beverage industry. It was to essentially separate CO₂ from the off gas of oil refining, and it would need to be very pure if that's the source of CO₂ we're going to use for carbonated beverages. It's not that it's the best technology, but it is familiar and low-risk. If we can think of the new generation of engineers and new approaches, then maybe we can get the costs down to something that's more reasonable.

We keep focusing on these dilute solutions, whether it is coal or natural gas, but there's also industry sources of CO₂, which are a small fraction of the emissions, where the CO₂ tends to be much more concentrated. We may be able to start with this low-hanging fruit and advance technology, get prices

down, and then apply that technology learned to the dilute systems. Maybe one day we can use it for approaches to bringing down the cost of direct air capture, which ranges from \$600 to \$1,000/ton.

STEVE SYMMS

You mentioned natural gas. I've been told that the Chinese don't run the scrubbers all the time on their coal-fired plants because of the cost. Secondly, how much, if we really concentrated on moving into natural gas, could we do on this overall big picture?

JEN WILCOX

When I was talking about natural gas versus coal, I was just talking about the CO₂ concentration in the exhaust. Although the natural gas produces an exhaust that's more dilute in CO₂ than coal, because natural gas is less carbon-dense, the rule of thumb is that you emit about 50% of the CO₂ emissions from a natural gas process than you would from a coal-fired power plant. It depends on where you draw the box. That scenario is if you draw the box around a power plant, but suppose you draw the box looking at the recovery of natural gas versus the recovery of coal. When you recover natural gas and are thinking of the wells, pumps, pipelines, and gauges, there's a lot of leakage potentially associated with it. There are some cities that have accelerated plans for replacing their pipes so that you don't get this leakage.

If we look at drawing a larger box and we include natural gas leakage, since natural gas has a higher global warming potential (about 25 times that of CO₂, depending on what timescale), then there are some who say that natural gas is dirtier than coal. The point I want to make is that this is also an open research question and more work needs to be done to close the gap between bottom-down approaches versus bottom-up (at the wellhead) approaches, and we need to understand, quantitatively, what those methane emissions associated with leakage look like. If we can know that number better, then we can conclusively say that natural gas is a cleaner approach than coal. Right now, how much cleaner it is than coal is still an outstanding question. Until we figure out the leakage issue, it's a difficult question.

REID DETCHON

We have three expert witnesses here – Brenda Ekwurzel from the Union of Concerned Scientists, David Goldston from the Natural Resources Defense Council, and Andrew Deutz from the Nature Conservancy. Then Ernie Shea will say a few words about changes in agricultural practices to capture more carbon in soil.

Jen, you see the potential for soil capture at something like five gigatons a year. How aggressive is that? Was that using state of the art capture practices globally or a more realistic scenario?

JEN WILCOX

That's various sources. From 2014, the IPCC had a number of 5.2, so we were using that number, but it was in agreement with other research. Some researchers had lower numbers – Tillman and others from 2006 had between three and four. There were different numbers out there, which is why we have a range. Those numbers are taken directly from the literature, and they go through a variety of techniques associated with low tillage and also no tillage, afforestation, and reforestation.

ANDREW DEUTZ

I want to talk a little about the biologic sequestration potential, which we have spent some time trying to quantify. Land use right now accounts for about 24% of global emissions. We've done some science, and we get similar numbers. Between decreasing emissions from the forest sector and agriculture sector

and increasing forest restoration, we can easily get between 3.5 and five gigatons a year, which basically means we could solve about a quarter to a third of the annual emissions problems by improving the land use sector. You can get to a theoretical potential of about 62% of the problem or about eight gigatons a year, and it's relatively inexpensive. So in reducing emissions from deforestation right now, the spot price is about \$5 a ton. For reforestation, the costs are anywhere between \$10 and \$50 a ton. In Beijing, we're generating carbon credits that are selling on the Beijing carbon market at about \$35 a ton; in the U.S., they are selling into the voluntary market for about \$18 to \$20 a ton. The U.S. is outcompeting China on forest carbon credits.

The biggest pools of carbon in terms of the biologic systems are forests – we can get about half the benefit there. In the agriculture sector, row crop agriculture is about another quarter, and then there are three other pools: grazing land, peat lands, and blue carbon. Our scientific and economic understanding of forests is the best, of the agriculture system is a little less, and it goes down from there. I'll give you two examples from the agriculture sector. Our look at the science on no-till practices show the costs are anywhere from negative to about \$100/ton. Improved rice management can get you a big chunk, particularly because you're dealing with methane as well as carbon that can get some significant scale at less than \$10/ton.

There is a huge underutilized potential to improve the biological sequestration capacity. Right now, there are 58 countries for whom the land use sector is their majority source of emissions – including big countries like Brazil, Indonesia, Vietnam, etc. The National Academy of Science did a useful thing in changing the language to climate intervention and was also helpful in separating the two different reports. We'd be happier to go one step further and differentiate the chemical and mechanical carbon sequestration opportunities, which is really the domain of the engineers, from the natural carbon storage opportunities, which is the domain of the ecologists and biologists. They're a lot less scary and make a lot more sense when you talk about conserving tropical forests, restoring forests, and improving agricultural practices to both increase productivity and increase carbon uptake. In most cases, they are cost-effective compared to the alternatives.

There's a lot that can be done and that we will be pushing for in Paris that we're already seeing in a number of country's INDCs, and that we hope to see in the post-2020 world. We need to help nature in order to help us solve the problem.

TIM WIRTH

Can you break down the barriers to each of these? To get from where we are today to the ideal you imagine – what are the greatest barriers, where would the greatest return be to break down those barriers?

ANDREW DEUTZ

The biggest and cheapest pool is standing tropical forests. Answer number one is to stop deforestation – that comes down to looking at a number of drivers among a handful of commodities. It's mainly beef, soy, palm oil, and other land management practices. It's a combination of a carbon price, together with improved land management practices and big shifts in commodity supply chain requirements. Unilever is saying they want to get deforestation out of their supply chain. McDonalds and Walmart are doing the same thing, particularly in their beef supply chain. Those combinations of things can get you to a 50% reduction by 2020 and no net deforestation by 2030. From there, it will vary sector by sector, geography by geography.

DAVID GOLDSTON

I'm going to go back to albedo modification. I want to underscore the reasons to do the research besides thinking that this is actually something we want to engage in. Some of it is figuring out why we might not want to do this. The other is, as Dave mentioned, if other countries (as well as non-state actors) wanted to engage in this, how would we even evaluate whether this is something to worry about or whether something happened that actually made a difference? Someone engages in albedo modification, and then another country takes offense that it's caused some problem there – how would we even know? So, there are many reasons to do this while we're still skeptical of the value of it.

The research agenda needs to include social science as well. One of the trickiest questions that many reports note is needed, but don't quite develop, is the governance issue – both domestic and international. It's already coming up in many international forums. What needs to be done on this? Rafe mentioned this one question that was in an interview with John Holdren that caused concern – the Administration has been in this posture of, "We'd really like to do this, but we need the okay that we won't get beat up", but it's not clear what 'okay' would be enough. Several environmental organizations have made clear that they're fine with the idea of research. I think hearing this from more places, and actually figuring out what kind of research agenda there should be, and pulling out what things are geoengineering research – there's already a push needed for that.

On the overall politics of this, it's kind of orphaned. Those who are pushing for mitigation, or even mitigation and afforestation, are nervous about it being used as an out. Those who don't believe climate change is real obviously haven't been fooled into saying that it's a great way in. The question is, where is the emphasis on this going to come from? I think it has to come from those of us who think the problem is real and that this does potentially raise geopolitical issues that you ought to have some knowledge to address.

Most of the issues on science funding now are pure budget questions, but the House has taken aim at all geoscience research for a mix of reasons. Mostly as part of an overall attack on science related to climate change. This a reversal of what it used to be: Those against climate action used to say, let's do the research instead. The overall fate of geoscience will have an effect on this. I do think there needs to be more voices raised on the need to create a more conscious, open, overt research program on this that is not based on the assumption that we're about to use it.

BRENDA EKWURZEL

I'd like to make three points: research, research, and research. The reason is, if you look at the cost per ton of CO₂, and you're looking at a process that was started in the 1930s or '40s, we're working on old technology, and we could use an injection of research to presumably bring the prices down for carbon dioxide removal. With regard to when we combust fossil fuels, we create these tiny particles that go up into the atmosphere, and a lot of them reflect sunlight – they're known as aerosols. We absolutely need to beware the cautions of albedo modification at the same time; we really need to understand from a basic climate standpoint how these aerosols are acting. We are not feeling the full brunt of what we've done with carbon dioxide in our atmosphere.

When we run models, it's incredibly scary when you take away the offsetting from the aerosols, and it's gone very fast. If we are weaning ourselves off of fossil fuels, what does that mean? Just from a climate science and rogue actor standpoint, we have to understand the aerosols better and need to invest in research. Luckily, in the U.S., we may only have 2% of the surface land area, but it's still a very important

2% because it spans many latitudes. USDA is going around the world doing research, and if we inject money and research in, for example, blue carbon in the exclusive economic zone around the United States, some of those carbon dioxide removal methods would be putting it into the ocean and neutralizing it so you don't further make the ocean sour. We need more research on that because of the amount of storage potential it has. Those are very tantalizing numbers, but they could be wrong because we haven't invested enough in the research to see if they could be at scale.

TOM DASCHLE

What is needed to be effectively engaged in research?

BRENDA EKWURZEL

There are a few people who could do a lot, even at the scale of the National Science Foundation, which has been atrophying. There's many scientists that are being underutilized in the government. If we were to fund the existing infrastructure, we're sitting on a lot of good ideas. Much of the good back-of-the-envelope science could be run before we even go to field scale. It's cheaper to invest in the brain power of the nation.

TIM WIRTH

If we brought our R&D budget back to where it was 10 years ago, are there some rules of thumb for this? Clearly climate science is not something that will get funded by itself, it's part of an overall commitment to R&D for which there seems to be a diminishing appetite.

BRENDA EKWURZEL

We were on a doubling of the budgets, both health and science, and now we're retrenching.

DAVE TITLEY

There's an iconic graphic, the American Association for the Advancement of Science (AAAS) keeps up on their website – in constant dollars, non-defense R&D funded by the federal government. When President Kennedy said we're going to the moon, you could watch the line go up right until we landed on the moon; you can see in the energy crisis of the early '70s, we invested. If climate is as big a deal as I think most of us see, you cannot see that in the U.S. non-defense research and expenditure, it just doesn't show up. We have this rhetoric, but we don't have the action. I would address your question as, "How do we narrow the error bars on what Brenda was saying to the point where we actually understand what is signal?" Frankly, we don't invest in it right now.

DAVID GOLDSTON

For a lot of the initial research, you need to understand more of how the climate is working, so it's not just for modification purposes. The estimate of the range of possible temperature changes because of climate change has not narrowed in a long time. Aside from the Apollo project, the percentage of money that goes to R&D doesn't change very much. The biggest determinant of the size of the research budget is the size of the domestic non-discretionary spending as a whole. The percentage of that doesn't vary a lot – in fact it hasn't much since 1960. This is part of the overall spending debate, there's no way to deal with it just as research.

STEVE SYMMS

I was fascinated with Andrew's points because people can see what you're talking about by planting trees, they can understand it. How much would it cost us to restore the way we used to manage the

national forests? Now we pay people to fly airplanes and drop chemicals on the fires because we don't manage the forest – it's a scandal. We burn off millions of acres of the forest every year out in the West. What would that cost us? To me, that would be a good way to reduce carbon, to get the forests managed again. We're paying to do it, but we're just not doing it.

ANDREW DEUTZ

One quick anecdote: We're working with the city of Santa Fe to create a water fund, where the municipal water utility is paying for improved forest management on federal lands. This came to be because there was a forest fire a couple years ago that produced several inches of ash that washed into reservoir and cost several million dollars to clean up. The city did the ROI calculation, and it was a lot cheaper to pay the federal government to improve the forest management than to clean up the watershed every time there is a forest fire.

STEVE SYMMS

I don't blame anyone for what's happened, but if you don't have a corporation that can build all the roads and go make a bid for the timber, you're buying the timber from a monopoly seller. The little mom and pop that has one logging rig that can go out there and cut some trees down and bring them out to the road, they can't operate any more. We've done something by our bigness that's wiped out what used to be environmentally well-managed. I don't know how you win that political battle because you run into political opposition.

ANDREW DEUTZ

There's a political coalition we're working with on this. What's happening is forest fires are accelerating, so the Department of the Interior and the Forest Service have to raid other budget items to fight them, so the conservation we want to see at TNC isn't happening. So, there's a conservation case for it as well as a timber case for it.

REID DETCHON

Ernie Shea has been actively involved in how the agricultural sector can make more of a contribution on the soil capture of carbon – so Ernie, over to you.

ERNIE SHEA

There's a lot we don't know and an enormous amount of work to do, but there's some good news coming out of the agriculture sector. There is an increasing body of evidence from work being done by the soil carbon modelers showing that agriculture feedstocks grown for feed, fiber, and energy – bioenergy solution sets – are also capable of delivering pretty significant carbon sequestration services simultaneously. We've been having a conversation with the agricultural community for a decade about how they can deliver terrestrial solution sets to feeding the world's population, to providing energy that's cleaner, and now, part of the conversation is increasingly how we can help reduce carbon emissions directly through biofuels and simultaneously sequester carbon when we grow crops sustainably.

At South Dakota State, Dr. David Clay has had a fairly long-term research program involving 120,000 individual plots. What they've shown is that continuous corn produced under no till – not reduced till – is sequestering significantly more carbon than anyone ever realized, in the order of magnitudes greater than native grasses. It demonstrates that bioenergy solution sets can provide multiple benefits that have not been valued. They aren't the silver bullet, but they can contribute near-term, lower-cost solution sets. There's a lot of variables on the amount of carbon that can be sequestered through a given

solution set, depending on agricultural practices, the crop being raised, the soil, and climatic conditions – they all affect the amount of soil carbon that’s actually sunk. We’re learning more as we go along.

One of the most exciting changes in the farm community is that there’s an increasing focus on soil health; it’s a lot about the organic content of the soil. When you manage soil health to produce food, feed, fiber, and energy, you start to have a conversation about a different type of business that we’re in. We’re not just in the business of producing crops that are grown from markets, we’re producing things below ground in the form of sinking carbon and improving the organic content of soils, which is part of our solution set for dealing with climate change. There is a sea change taking place across farm country, and a lot of it has to do with soil health, which they may initially think about as how they can improve productivity of crops while reducing inputs, but we’re helping them understand that part of that soil health is also a climate change solution set.

Our conversation is increasingly morphing into climate smart agriculture strategies. How can we deliver multiple solutions to global challenges? The North American Climate Smart Agriculture Alliance that’s just being formed is an example of the best and brightest minds coming together to think about how we can deliver climate solutions at the same time that we deal with the adaptation challenges and becoming more resilient. It’s a fresh start for a conversation with the farm community about climate change. It’s also a way to start talking directly about mitigation services and the enabling policies that are needed for those solution sets to be fully realized. The numbers we’re talking about here are not insignificant in terms of the potential of terrestrial resource bases to contribute solution sets. If we can get the right enabling policies in place to create value for the carbon that we’re capturing and sinking through photosynthesis, I think it’s a different conversation. We’ve got a long road, but we’ve turned a corner.

RAFE POMERANCE

What the Academy has basically proposed is a portfolio approach – reduce carbon from energy, utilize carbon sequestration, and think about albedo modification. All of it requires R&D. We have a small agency called ARPA-E, which is high-risk research, modeled on the Defense Advanced Research Projects Agency (DARPA). This effort needs to model its budget on DARPA, which is \$5 billion a year for the Pentagon. We need \$5 billion for the planet. We need the R&D to solve this.

TIM WIRTH

But we’re not going to get a pot of money saying “climate change.” What does AAAS give as the total dollar amount, not the percentage, that they say has to be running through NIH, NOAA, and NSA?

DAVE TITLEY

All non-defense is \$66 billion as is, and 50% of that is health.

DAVID GOLDSTON

In some ways, the Augustine report has been a barrier to this, not intentionally, but if you look at what basic research advocates in Congress have done, they’ve said, “Let’s take these things that are related directly to competitiveness and double them and most parts of NSF (but not geosciences), NIST, and DOE and make sure that we’re not wasting money on other kinds of science not related to competitiveness.” Some of the enthusiasm for the Augustine report has boomeranged in terms of these kinds of things which are viewed as not directly related to technological competitiveness. Their argument is that a lot of this is about innovation and could be linked up, but that hasn’t been the way the arguments have gone.

TIM WIRTH

My guess is that if there's not a consensus number that unites all of the research elements of the community, then you're not going to get from here to there. This is potentially a powerful political community, if you look at the governing boards of state and land grant universities and all the private universities in the country, that's a potent political force that has never been organized to get together. I find myself frustrated by the R&D community's inability to make its own case – they do specific pieces of it, but then they start to squabble with, well this might be included, that might be included – and you're sitting there with a tired Appropriations Committee, and what are you going to do, Daschle? You're going to say, "Next."

KALEE KREIDER

They're also competing on the health side; many of these institutions have their medical schools wanting a cut. This is part of the reason we look at AAAS numbers together, but once you start to raise both sides, they start competing between.

DAVID GOLDSTON

It's gotten better. I spoke with a university lobbyist last week who argued that on geosciences the climate is bad news, we shouldn't talk about it, and we should just talk about the oil and gas. I argued against that, because if you run from this, you'll just be chased.

RAFE POMERANCE

The Academies have left us with a framework for how to build that R&D commission, and at some point the politics will have to support that. ARPA-E is only \$200 million a year.

TIM WIRTH

I'm all for ARPA-E.

TOM DASCHLE

One counterintuitive matter – one thing we could do is to restore the earmark. Earmarks are critical, and we've taken away any real opportunities for members to weigh in on behalf of their institutions and their priorities. I think that's a huge mistake.

TIM WIRTH

I agree, you've taken away a major tool for governing the institution.

STEVE SYMMS

I couldn't agree more, the highways to hell are paved with good intentions. The way we've managed our national forests – just to look at one issue, everybody had good intentions. We had a professor at the University of Idaho that wanted to homestead the national forest. He spent his whole life working out this program so families could move into the national forest, but you had to open up the roads. In order to 'save the environment', we stopped building roads, so now the forests just burn, and no one can get to them.

REID DETCHON

We're back again on June 15 to talk about ocean acidification, and you'll see many of the same themes in a month.