OK, well, it's a pleasure to get a chance to introduce Howie and his book. You know, we often say that the climate issue is a marathon, not a sprint, but a marathon. And this gang knows that there's no happy end to that marathon without some version of carbon capture and storage, almost all the scenarios. And one way or another, you don't get there without capture and storage.

And Howie has been running a marathon himself on this issue for almost three decades here at MITEI, and in various organizations before MITEI. And what he's done here at the invitation of the press is to put that personal experience down for a broader audience. We just need so much of this kind of thing. And what Howie's done, I think, is really, really magnificent, in that the way that it brings together the technology at a level that it's not for the grade school students to do. It takes some level of scientific knowledge to read it, but for a wide audience on the technology, and serious about the economics and very good on the politics and on the history of all of this, and told through his experience of three decades doing this.

And because it's got this personal style, you learn unusual things. For example, why is it when you spill gravy on your shirt, you can't clean it up by dipping a piece of cloth in your water glass and cleaning it off. What else is at work? Read this book, and you'll find out.

And another thing is that we're in an era now—we know in the country, we're in an era where we're all concerned with the degradation of the laws, that we're in a nation of laws and we're fighting to preserve that. One of the hidden stories of this book is that Howie is preserving the second law of thermodynamics. Buried in a chapter in this book is a controversy over this issue that's been going on for many years. And Howie has fought the good fight.

All that is encapsulated in a little volume which is imminently readable and available to a large audience. And so, congratulations, a great job, and I'll turn it over to Howie to talk about.

[APPLAUSE]

Thank you very much, Jake and Martha, for the nice introduction. And thank you all for coming. And thank MITEI for organizing this. And what I am going to do today is sort of walk through the book and do a few readings, and give some context to them. And hopefully, I can do it and have time for questions too. So first time I'm doing it like this, so we'll see how the timing works all this. Let me grab the slide here.

So first, let me tell you how this came about. It was almost two years ago now, just in my office, a normal day. And I get an email from MIT Press. So this was like November of 2016, says, would you be interested in writing a book for the essential knowledge series, which this is a part of? And it actually was very good timing for me, in that the consortium that I had run for 16 years, we had just finished. And I was sort of looking for a new project. And so it was perfect timing, so I said yes.

I had to go through the proposal process, which took about three months where I had to write a proposal and get it reviewed. And actually, that was very good because it let me think through the book, and the structure of the book was set during that. And then, February of last year, I started writing. And the writing process took maybe about six months and then there were some other things we had to do. We were originally trying to get the book in September of last year to get it out this spring. But then, they told me they want it in the fall release of this year. So my deadline got extended to December.

So I had everything going in December, and I waited until a few weeks ago when the book came out. A few things happened. I had to do some copy editing I had to review, and the page proofs. But basically, I just had to sit there for eight or nine months until the book came out. So sometimes, these things you do, and then it becomes almost anti-climactic. But it's good it's out. And I'm going to walk through it. I'll walk through it a little with you.

So this is eight chapters for the books. And I'll touch on each of the eight chapters as we go through this that press like a short title. So the title is Carbon Capture, but I use that synonymously with carbon capture and storage, or CCS, throughout the book. So it's not just capture, but the broader suite of technologies.

So let me go back a second here. Let me start with the first reading here from the introduction. I just had cataract surgery, and I'm waiting for a new pair of glasses. So I can't see. I can't read with these glasses, so I have to take them off.

The burning of fossil fuels, namely coal, oil, and natural gas, releases carbon in the form of carbon dioxide. The CO_2 becomes part of the exhaust gases that go up the smokestacks of our power plants and factories, out the tailpipes of our automobiles, and up the chimneys of our homes. These CO_2 emissions are a major driver of climate change. The idea behind CCS is to capture the CO_2 before it's released to the atmosphere.

Capture technology exists today with its roots in industrial processes that cleaned up gaseous products by removing acid gases like carbon dioxide and sulfur dioxide. The question then arises, what to do with the CO_2? There are some opportunities for using it, but they are limited. As a result, most current CCS strategies call for the injection of CO_2 deep underground. This forms a closed loop, where the carbon is extracted from the earth in the form of fossil fuels, and then the carbon is returned to the earth in the form of carbon dioxide.

So for the first slide here from the first chapter of the book, sort of reiterates in a very simplistic form, the climate system and what we can do about it. So we start here with human activities, energies out of human activities including energy use, but also agricultural practices and other activities. We release greenhouse gases into the atmosphere, and their concentrations are increasing. This, then, affects the global temperature which is rising and has impacts on Earth's systems in all sorts of manners, whether it's bigger storms, droughts, floods, things with vector-borne diseases, and a whole list of items can happen, maybe I should say on the Earth—so things like sea level rise, and that now comes back to affect the human activity.

So this is a loop. And we also have another arrow that connects the atmosphere concentrations of the Earth systems. That arrow goes both ways. So for instance, one thing is the oceans and the vegetation, the forest can take CO_2 out of the atmosphere. And in fact, the ocean is a big sink, otherwise our atmosphere concentrations would be larger. But it can go the other way. And people fear if the temperature warms up, there's a lot of methane contained in, say, the permafrost. And if that melts, that methane can go back into the atmosphere and have a big impact.

So what are the ways we can intervene in the system? The first is mitigation. And that means we will reduce the amount of CO_2 in the atmosphere that we emit from human activity. And carbon capture and storage is one of the major mitigation pathways.

You can also have adaptation, which is something that's probably going to be necessary. So if we have sea level rise, you may have to have flood control and maybe dikes to help preserve different human activities and property. Another area that I'll talk a little more about here is carbon dioxide removal, actually taking the CO_2 out of the atmosphere and storing it in, say, the ocean or in deep geologic reservoirs, or in the soils and vegetation that you can do.

And finally, there's something called solar radiance management, which is trying to, say, maybe put a little sun shield on the Earth to reduce the incoming radiation and sort of counterbalance the warming. And there was a National Academy study back in 1991 about this thick, very heavy. And they had about a 10 page appendix on it talking about different—what's called—geoengineering options. And of course, this is what the press loves. And there was a two page article in Newsweek on that big report that just talked about that 10 page appendix that was caught on the wings of Icarus. So it's something.

But here's what I say about solar radiance management in the book. By far, the most controversial intervention strategy is solar radiation management. The idea is to block incoming sunlight to cool the Earth in order to counterbalance the warming caused by enhanced greenhouse effect. The inspiration for this strategy comes from nature, where volcanoes cool the planet by spewing ash and sulfates high into the atmosphere. This cooling can last for a year or two. In New England in 1816, is known as the year without a summer. The cause of these unusually cold temperatures was an event on the other side of the globe, the eruption of Mount Tambura in Indonesia in April 1815.

More recently, the eruption of Mount Pinatubo in the Philippines in June 1991 depressed global temperatures by about 1/2 a degree Celsius for a couple of years. Solar radiance management mimics nature by injecting particles high up in the atmosphere to block incoming sunlight.

I look at solar radiance management as a Hail Mary pass in football. It rarely works, but when it's your only option, you try it. I think the best strategy for human kind is not to get in the position where we need to a Hail Mary pass. That means we must mitigate, mitigate, and mitigate some more. That's where carbon capture can make a big contribution.

Let me go to the next slide. And this slide here shows how much fossil fuels we have. So this is chapter two. And this is what they call recover reserves. This is an economic thing. These are what's on the books of the oil companies, for instance. And this is how much we're pretty sure we have on the ground that we can recover and burn, if we want.

And these are the carbon budgets, how much we're allowed to burn to stay below 2 degrees C or 3 degrees C. Actually, I think since I did these numbers, this new report coming out in a couple of weeks have upped those carbon budgets a little. But the idea is the same. So if we want to control climate change and stabilize at these areas, we have to leave a lot of fossil fuel in the ground.

So let me let me do a few readings from the fossil fuel chapter—first, on a carbon footprint. Because fossil fuels are ubiquitous, just about everything we do has a carbon footprint. Every day, we make dozens or even hundreds of decisions that affect that size. This includes what we eat—because meat has a higher carbon footprint than vegetables—how we get around—either by automobiles, mass transit, bicycling, and walking, they all have different carbon footprints. When we go shopping, everything we buy makes an impact—from the manufacturing of the item, to its transport. The impact of heating or cooling your home depends on the kind of fuel you use, the efficiency of your heating system, the insulation of your house and the setting of your thermostat. Turning on the television or computer adds to your carbon footprint as well.

There's always been questions about how much fossil fuel we have. When I first got my first car in 1974, there was something called gas lines. Some of you older folks here remember that. We thought we were going to run out of oil. There was something called peak oil. And everybody believed it, except a few people. And there was a professor here, Morris Adelman, once again, which some of you know, who I love talking to about this subject and others. And so I pay homage to Morris in my book. I'd like to read a couple of paragraphs about Morris. Professor Morris Adelman, now deceased, was an economist at MIT and an expert—in my opinion, the expert—on the oil and gas industry.

In 2001, Morris gave a talk in a meeting I was running. He started by saying, people always ask me when we're going to run out of oil. The answer is never. You can hear some laughter from the room, but Morris was not trying to be funny. He was quite serious. In his view as an economist, if we started to run out of oil, the cost would rise. At some point, the costs would rise to a level where we would have found substitutes for oil, leaving the remaining oil in the ground. We will never extract every drop of oil from the Earth.

Through much of his career, Morris was a voice in the wilderness. People wanted to believe in peak oil because it made so much sense. I vividly remember a talk we had after another prediction on peak oil got a lot of press. I asked how people could still believe in a theory that was always wrong. The proponents always blamed their failures on faulty data. Paraphrasing his answer, oil follows the laws of supply and demand just like every other commodity. However, people don't view oil simply as a commodity, they view it like a religion.

So the last thing I'll say on fossil fuels is what happens if we go ahead and burn all those fossil fuels? What would that do to the environment? If we did burn all our recoverable fossil fuels, emitted the CO_2 to the atmosphere, the global temperature would rise by about 9 degrees centigrade, that's about 16 degrees Fahrenheit. Remember, we're at about 1 degrees centigrade now. And there's a debate how much we're seeing is due to climate change. But needless to say, 9 degrees centigrade is probably not where we want to go.

So, let me go into carbon capture now, and have a reading that starts at the chapter here. In the high desert, about 250 kilometers Northeast of Los Angeles is the Searles Valley Minerals plant. This plant produces a number of chemicals, such as soda ash, from the brines that they mine. The manufacturing process requires significant quantities of carbon dioxide to carbonate the brines. And being in a remote area, it would be very expensive to transport CO_2 to the site. Carbon capture, as it turns out, provides a cheaper solution.

In 1978, then owner, North American Chemical, developed a process to capture up to 800 tons per day of CO_2 from a coal-fired boiler. This process, based on amine technology, was originally patented in the 1930s. However, 1978 was the first time amines were adapted for use on a coal-fired boiler exhaust, known as flue gases. In fact, it was the first implementation of carbon capture on any type of boiler.

Constructed well before people considered carbon capture for climate mitigation, this project demonstrated that carbon capture was feasible on flue gas from fossil fuel combustion. So if we go to the next slide, here, what we have is a little schematic of the amine process. I'm not to go in a lot of detail here, but at the heart of the process are two columns. This is called the absorber column, and this is called the stripper column. We have the flue gas from the power plant coming into the bottom of this column. And this column was packed with materials that create a lot of surface area for contacting between the flue gas and the solvent, which, in this case, is an amine, that flows down the column.

And what happens is the amine attracts the CO_2 out of the flue gas and chemically binds with it. So coming out of the column, you can capture 90%, 95% of the CO_2 from flue gas and send it here. Now, the solvents are expensive, so we want to reuse it. So we have a stripper column where we drive the CO_2 out away from the solvent, so we can recycle the solvent back to the absorber.

Here, we generate steam. So this rebar there provides energy to generate steam to go up the column. The solvent comes down the column. And the reverse happens. The steam strips the CO_2 out of the solvent, and brings it to the top of the column. Here, you have water and CO_2. Water is easy to separate, mainly by condensation. And you do this during compression. And you compress the CO_2, to be then transported by pipeline. And you come out with CO_2 that's over 99% pure.

So let me just tell you why we use amines with this little reading here. Of the many potential solvents for chemical scrubbing of CO_2, presently, amines have proven to be the best. It's a Goldilocks solution because the attraction between the amines—a weak base—and CO_2—a weak acid—is not too strong and not too weak, but just right. If the attraction were too weak, it was out in extremely large and costly absorbers. If the attractions were too strong, a simple temperature swing would not be able to regenerate the amine.

I should have mentioned in doing this process, that this operates at a cooler temperature, about 50 degrees centigrade. And this operates at a hotter temperature, about 110 degrees centigrade. So you regenerate it through what's called a temperature swing.

So, now we've captured the CO_2. And the question becomes, what to do with the CO_2? That is the question. Should we put it back in the Earth from whence it came? Should we sell it as a feedstock to make useful products, thereby recouping at least some of the cost of capture? Should we return it into rocks, stabilizing it for millions of years? Researchers are exploring all of these options.

The one that holds the most promise is putting it deep in the Earth. It's called geologic storage. Geologic storage of CO_2 is the mirror image of oil and gas production. Instead of drilling wells into the Earth to extract oil and gas, wells are drilled to inject the CO_2. So one question people always have when we put the CO_2 into the Earth is, will it stay there? And this is a diagram from the Intergovernmental Panel on Climate Change, a special report on carbon capture and storage, and shows the mechanisms that keeps the CO_2 in the ground.

Now, three of these mechanisms are pretty easy to explain. This structural and stratigraphic trapping, well, that just means it's like you have a container in the ground to keep it in. So you generally inject the CO_2 into sandstone, some porous layer and permeable layer like sandstone. And then, a lot of times, above the sandstone layer, you have a layer of shale where the CO_2 can't move through. So it acts like a cap, it's called a cap rock, and keeps the CO_2 in place.

What we mean here by solubility trapping is these layers have water, and it actually brines—very salty water. And the CO_2 can dissolve into the water. So solubility, over time, the CO_2 will dissolve into the water in the formation. I should mention these formations are generally fairly deeper than 800 meters. And finally, mineral trapping talks about a longer term mechanism, where the CO_2 actually reacts with the rocks in the formation and precipitates out, usually, as a carbonate rock.

So those mechanisms, I think, are fairly straightforward to understand. But how do you talk about residual CO_2 trapping? And Jake sort of alluded to this. And I will read that section here. Capillary trapping, sometimes referred to as residual trapping, refers to the CO_2 being immobilized in the pore space as a plume moves through the formation. So it's getting trapped in the porous space of the sand in the formation.

It's a function of water and CO_2 competing to move through the small pores between sand grains. A capillary trapping situation the most of us can understand—can relate to—is the dripping of oil on our shirt while eating. You try to rub out the stain using water, but that will not work. The oil was trapped in the holes between the fibers. In this sense, capillary trapping is a very secure storage mechanism.

So one of the challenges of writing this book is trying to explain pretty complicated scientific things. In fact, first time I was introduced to capillary trapping, I had a hard time really understanding because they start talking to you, throw out words like relative permeability, and throw all these mathematical equations at you. And I will say, I credit this to Sue Hovorka at the University of Texas. I didn't think that up myself. So over the years, I have stolen. It's like a good comedian, I steal things from lots of people.

So, we actually have examples of CO_2. And so, I have a chapter on what I call CO_2 in action, about some of the big installations. And this is slight in there. So let me read about this. Sleipnir is the name of an eight-legged horse in Norse mythology. It is also the name of the world's first commercial CCS project.

Located in the North Sea about 240 kilometers off the coast of Norway, Sleipnir has been storing about 1 million tons of CO_2 per year since October 1996. The source of the CO_2 is from the natural gas produced at the platform, where CO_2 concentration is about 9%. Before shipping the gas to customers, the CO_2 concentration needs to be reduced to under 2 and 1/2%. At many gas fields around the world, this is accomplished using amine technology. Unique to Sleipnir, however, this is the world's first installation where the CO_2 removal takes place on an offshore platform. So that's this platform here is where they're processing the CO_2.

The captured CO_2 was then compressed and injected underneath the platform into a terraformation, a sandstone layer lying 1 kilometer beneath the North Sea. While there are commercial carbon capture projects that predate Sleipnir, their motivation was to produce CO_2 for use in commercial markets. Sleipnir marked the first instance of carbon dioxide being stored in geologic formation because of climate considerations.

More recently, there's been two projects at coal-fired power plants that capture the CO_2—one up in Canada, and one in Texas. The Texas one is Petra Nova that we see here. And I think it's interesting, these projects, to understand the motivation of why the company does it. So this is a plant owned by NRG. And once again, it uses amines to separate it. But I'll talk a little about why this project got the green light. There were some government incentives and stuff. But still, why did NRG go ahead of it? And it was really one man that really drove this project, and that was David Crane, who was the then CEO, no longer with NRG. And so I'll read a little about that.

At initiation, this project aligned well with NRG's business strategy. The CEO of NRG at that time was David Crane, who strongly felt the future was in clean energy. As he said in his resignation letter, the new frontier of the energy business that I pushed the company into was then and is still now in the long term best interest of the company's employees, its shareholders, its customers, and the earth we all inhabit—a company that aspires to growth. There is no growth in our sector outside of clean energy, only slow but irreversible contraction following in the past of fixed telephony. So

David Crane was a visionary, but maybe he was a little ahead of his times, as some of these visions got him forced out of the company, unfortunately.

But next, I want to move into the chapter on negative emissions. And this is something that's going to get, I think, a lot more play when the IPCC report on 1.5 degrees C comes out—well, they have a press release October 8 on it. And negative emissions will be in that report. And probably, as I say, just like the press likes to pick up on things like geoengineering, I think the press will pick up on negative emissions also.

So let me start with a little introduction. To remove allergens and other contaminants from the air inside your home, one can buy an air purifier. Just imagine if we had an air purifier to remove CO_2 from the atmosphere. We can go about our business as usual, spewing CO_2 from our cars, homes, and factories, without needing to worry about reducing or eradicating these emissions. Our CO_2 air purifier would eliminate our climate change concerns, just as today's air purifiers eliminate our concerns about indoor air quality.

The idea is very seductive. As a result, interest has been growing in what is termed carbon dioxide removal as a way to address climate change. The concentration of CO_2 in the atmosphere is very dilute, about 0.04%—that's 400 PPM. Nevertheless, there are a number of technologies referred to as negative emissions technologies, or NETs, which can remove CO_2 from the atmosphere. How big a role NETs can play is a topic of considerable disagreement.

So, what are these NETs? And we have a list here. And the top two deal directly with carbon capture. And I talk about them more in the book—bioenergy with CCS. And that's the one that a lot of the big models are attributing most of the negative emissions to. Something called direct air capture, which I've commented on quite a bit as being actually, you can capture CO_2 out of the air with solvents and the like, but it's very expensive. There are some companies doing it. And just like any company doing it, they make a lot of claims. And every time they make a claim, it seems they get a lot of calls from the press wanting to counterbalance that claim a little. And this is, I think, where Jake talks about the second law of thermodynamics.

If you take something from a power plant and want to capture it, it's one thing. If you take it and dilute it by a factor of 300 and then want to capture it, it's going to cost you a lot more money. And that's just the way it is. There's other things. A lot of these are associated with biology such as afforestation and reforestation, things and the agriculture like changing your tilling practices, biochar, a very controversial thing. Then, there are some things that have to do with enhanced weathering, which are even more speculative, things like ocean fertilization, which I think there are still people that talk about them. I think it's fairly much off the agenda from a lot of people, at least, the environmental impacts, as well as we're not sure how well it works.

So these are the different negative emissions technologies. And I'll read a few things. So it's a very controversial thing, and especially, can we overshoot our 1 and 1/2 or 2 degree and bring us back? That's one of the big questions that's being asked. And there's a lot of papers in the literature. The numbers go all over the place. People are sometimes very optimistic, sometimes pessimistic. So let me read to you my view on it.

One way to view the role of NETs is as an offset. This means that the amount of CO_2 removed from the atmosphere generates credits that offset emissions elsewhere. That role exists today with implementation of local, national, and international climate policies, including the clean development mechanism of the Kyoto Protocol. These projects mainly involve afforestation and reforestation. With the publication of the IPCC's Assessment Report 5—which I'll refer to as AR5—the proposed role of NETs expanded significantly.

AR5 presented a number of emissions reduction scenarios, raising questions whether mitigation efforts alone would achieve the goal of stabilization below 2 degrees C. Policies around the world are developing too slowly. So realistically, there's not enough time to deploy the required mitigation technologies before the carbon budget associated with stabilization at 2 degrees C runs out. If that proves to be the case, the only way to achieve 2 degrees C stabilization goal would be to overshoot it and then eventually return to it by removing CO_2 from the atmosphere through the deployment of NETs.

Here's my view on NETs. Their role as an offset is very sound, with some deployment already happening today, and increased deployment expected in the future. The role of NETs to compensate for breaking the carbon budget and overshooting stabilization targets may be more hope than reality. However, the hope is being fueled by a big interest in developing and deploying NETs. More and more people are embracing this concept because the excuse is pushing hard policy decisions regarding emission reductions down the road.

However, despite this increase in interest in NETs, the technical, economic, and environmental barriers are real. There is a good chance we cannot count on NETs in the long term to compensate for our failure to do enough mitigation in the near term.

So I'll get moving into the penultimate chapter here, where I talk a little about politics and policies. But just to sum up what I see some of the real strengths of carbon capture and storage, some unique features of it is it produces dispatchable power—low carbon dispatchable power—as opposed to intermittent power from wind and solar. And it's much more dispatchable than, say, from nuclear. That's an important niche in our electricity systems.

It's the primary option for energy-intensive industry, like cement refineries, petrochemicals, and iron and steel, where things like renewables will have a very hard time fitting in—especially since a lot of these industries, CO_2 doesn't come from energy use, but from the process itself. It's the only mitigation technology that can rescue possibly hundreds of trillions of dollars of stranded fossil assets. The question is, will we really leave all those fossil assets in the ground? Will countries really develop policies to do that? This is a way we can use some of those assets, and also provides a major pathway to negative emissions when combined with biomass-fired power plants.

So those are some of its strengths. And I comment on the politics of CCS. As Jake said, I've been around a while. And well, I'll just read what I wrote. When I first started working on carbon capture technologies in 1989, I anticipated that the field would bring together both sides of the political spectrum. On the right, carbon capture meant we could address climate change without ending our use of fossil fuels. On the left, it meant another technology was available to list in the fight against climate change.

It turns out, that I could not have been more wrong. I did not foresee that over the years, climate change would turn into a very partisan issue in the United States. Hard to believe that it was Republican President, George HW Bush, who negotiated and signed the United Nations Framework on Climate Change. Just as astonishing, the US Senate ratified the treaty by the necessary 2/3 vote. How times have changed. The Right hates anything to do with climate change, even it could benefit fossil fuels. Similarly, the Left hates anything to do with fossil fuels, even if it could help mitigate climate change. One can say that carbon capture has become an orphan technology.

So I'm going to end the talk with talking about the future. And I'll start by saying, so what does the future hold for carbon capture? According to the great American philosopher and baseball player, Yogi Berra, "it's tough to make predictions, especially about the future." Taking this sage advice, I will avoid outright predictions, and instead explore key determinants for the future carbon capture—specifically, the evolution of climate policy and the evolution of energy technology.

So what I'm saying there is if you don't have good, strong climate policy, we don't need carbon capture. Carbon capture is there to address climate change. If we don't have policy that's going to lead us on a path to reduce our emissions of CO_2 in the atmosphere, we're not going to have markets available for climate to go. Evolution of energy technologies, there's a lot of different technologies that can play a role. How they evolve will be very important. Will there be a breakthrough in nuclear? We have this fusion thing at MIT. Will that to ever come to fruition? And I'm not staying up late worrying about that.

But there's all sorts of things that can happen, and it's very hard to predict the future in terms of energy technology. But you can say that innovation is going to be a key to solving the problem. So I'm going to end, and I'm going to spoil the book for you and read you the ending. But the journey is just as important. So here's the ending. Although I think it's inevitable we will see the 2 degrees C temperature stabilization goal, I do think we will stabilize at some higher level. I remain a firm believer that technological change will be critical in achieving this stabilization.

However, this change does not magically appear. It requires investments from government and industries and policies to create markets that provide the incentives to develop new technologies. What we are doing today is inadequate. We must pick up the pace and broaden the portfolio of options. We cannot predict the future very well, but the decisions we make today will shape the future. Our grandchildren and their children will judge us by those decisions. What will be our legacy? What type of world will we be leaving them?

And these sentences hit home, because yesterday, I got my third grandchild, so I'm right there.

[APPLAUSE]

About 35 years ago, I was on a radio program. It was a call-in show. And I talked about climate change. And we had some call-ins, and I must have talked about CCS because one of callers-in said, why don't we just store it in tires? When you inflate your tire, inflate it with CO_2. I was wondering if you had an answer for that.

[LAUGHING]

Oh, god.

[LAUGHING]

Only if they're tires for electric cars, John. Or we can invent something to take it from the tailpipe right into the tires. Yes? Well, I guess I'm not controlling. I'll let them control the mic.

Thanks for this presentation. Can you talk about some of the weaknesses of carbon capture, both storage and utilization?

Well, it costs money. It's not the cheapest option that you have. So cost is, I think, one thing. But I think a lot of the models show that if we are going to get down to stabilization, that the cost of doing it will be well above what it costs to do now. So that's one problem. I mean, in terms of the storage, we don't have a lot of experience. Now, all signs point that it should work, but really need a lot more experience doing it.

So it's sort of ironic that we aren't doing a lot of work on storage. So there are some things like Sleipnir. But in general, we don't have a lot of large scale storage demonstrations. What they've been doing mostly for storage is putting it into oilfields for enhanced oil recovery, which, in the long term, is not going to do it. They're doing it because of economics. And so the biggest cost of doing a storage project is the cost of CO_2. So we have all this CO_2 that we want to get rid of, but to do a storage project on it, it costs money because the cost is in capturing and basically concentrating the CO_2.

The demonstrations to date have been fairly positive. But it's both, I think you need to get more knowledge, but also, you need these demonstrations, I think, for public acceptance. Obviously, when you're talking about putting lots of CO_2 under the ground there where somebody lives, there can and will be questions. So I think those are some of the things. You're going to have to do pipeline networks, as we saw what happened up on the North Shore here in the Merrimack Valley. People are adverse to pipeline and infrastructures. But I would say for a lot of the technology, even if you want to do a lot of renewables, people talk about need for a lot more transmission lies a lot of infrastructure. So how you build the infrastructure in this time is going to be a big problem. So there's lots of barriers. I don't think any are insurmountable, but those are some of them. Yes? Move it up to there, then.

Oh. Becker and Jacobson have estimated the requirement for seasonal storage in connection with deep energy option. In Denmark, one of the efforts that they are making [AUDIO OUT] trying to develop electrolysis of CO_2 hydrogen [AUDIO OUT] methane and pump that into their existing gas distribution network. Do you have any idea about how many times more expensive [AUDIO OUT] natural gas made that way, compared to, say, Siberian gas from Russia?

Well, I don't have exact numbers. But it's a lot more expensive. I wrote a paper on utilization of CO_2, where we talk about things like they're doing in Denmark. And we actually compared it to, say, the carbon capture approach. And the answer is, until you decarbonize your electricity system, it isn't really worth thinking about. Because you need the energy to create the hydrogen, for instance.

So I don't have a number. But to me, it's very, very expensive. And the CO_2 that you're going to use, you need to get the CO_2 from a non-fossil source. Otherwise, when you make natural gas, can go back in the atmosphere. So you can't put the any new CO_2 in the atmosphere. It has to be a non-fossil source, which is either biomass, or this direct air capture. So it's not only expensive for the hydrogen and the reaction, but also the CO_2.

And every time you do these conversions, you lose energy. So that's more cost. So I don't have an exact number, but it's probably—I mean, it's way more than double. It's probably maybe even triple and quadruple.

Three to four.

Yeah, well, that could be true. I don't have the exact number. That sounds like a reasonable number. The front row, here are two questions. I'll let you guys fight over the mic.

Will it be necessary to do long time scale experiments to see how long CO_2 is trapped in the Earth?

Well, you don't want to wait to do the experiments before you actually do it because we don't have that much time to do the mitigation.

Was there a middle ground?

I mean, it's been discussed a lot. When I worked on the IPCC report, it was one of the questions that aroused. And the secretariat wanted an answer. And it was one of the two issues that caused bloody battles, shall we say. Utilization was the other issue. So they basically said, if you choose the right reservoirs—so put an asterisk there, whatever that means—they expect less than 1% leakage over 1,000 years.

So from the tests we've had so far, you don't see a lot of leakage. In fact, you don't really see any. So I think the real key there is doing the right sites. But we don't have the luxury of doing an experiment and waiting 20 years, and then be able to repeat it. Because we need to start doing the mitigation right away. And with the CCS, we're talking we want to start ramping up by mid-century. And then after that, I think you'll see more of it in the second half.

But I will say, there have been some natural analogs they've looked at. But geologic formations are so heterogeneous. There's going to be some that are not good, and you don't want to put it there. But I think a lot of them work pretty well.

Well, I was a little disappointed not to get more cost figures. Let me ask you, I was trying to take your processes and decompose them into an absorber phase, where the cost driver was the gross amount of gas, and a stripper phase where the cost driver was the amount of CO_2 that was absorbed. And I couldn't make the numbers match up at all. It would seem that if you believe your $1,000 per ton of CO_2 for direct air capture, but assign all the cost to the absorber phase—which is unrealistic—you've got only $0.40 per ton of air for the cost of absorbing this stuff, which would make all these processes look very different if that were true.

So you're talking about the direct air capture?

I'm talking about both. I can't make the numbers be consistent for these processes.

So if you do these today, if you do a plant like this today—because it's a first mover—it'll probably cost you on the order of $100 per ton. We've done a lot of cost studies that make you think you can do a plant with today's technology for maybe $60 a ton. A lot of the cost is here in the energy you use. 2/3 of the energy is steam for the re-boiler, another 1/3 is for the compression.

The absorber doesn't really use that much energy. It's a little blower to overcome the pressure drop, but it's capital cost. So as I said, if your solvent is too weak, its reaction is your absorbers are getting big and your capital costs go up. Well, it's hard to disassociate because it's one day process. It affects everything. So things that you do here affects how well you strip the difference between your lean loading and your—but if you want me to talk about when you go to direct air capture, what's the difference?

First of all, you can't use the temperature swing like this. What you have here is the partial pressure of the CO_2 in the air is a factor 300 different than it is from a power plant. So some people use stronger solvents like hydroxides, which means then you have to have a very complicated chemical process to regenerate the hydroxides.

There's one process that use solids amines. And they use sort of a temperature/pressure combination. They heat it up and then draw a vacuum. But in your absorber, you're putting through 300 times the amount of air. And well, it depends on your pressure drop. If you do the calculations, just a small change in pressure drop is a big change in cost, of energy costs.

It made me think [INAUDIBLE].

[LAUGHTER]

Well, yeah, I wrote a paper on it, so you could look at it. But you have to look at each specific thing. It may be, especially when you look at an avoided basis. But there's a whole range of things. The company in Switzerland, Climeworks, claims about $600 a ton. But they have some special things that make their process cheaper.

Hi. Congratulations. It sounds like a very good book. And the thing from what you've read that I think will be most valuable is the manner in which it's written.

What?

The manner in which it's written, very accessible. Because I think there's a tremendous need for a much broader audience than just highly technical folks to talk about these things and understand them. My only hope is that just like 10 or 15 years ago, a lot of things that are becoming very widespread now—[AUDIO OUT] that were being looked at [AUDIO OUT] in the sky, way too expensive, that a similar thing will happen with this, since some things like the industrial aspects of it are very hard to avoid. And I would just [AUDIO OUT] that not only do we have [AUDIO OUT] in the Carolinas this week, but today is the anniversary of Maria, v in which there are people who are still barely recovering from that. And last year, we had you know Harvey, Irma, Maria.

So I think the prospects, some people make light of it the prospects of truly [AUDIO OUT] increase or even beyond. I don't see how society is ready to deal with it. So I think—I'm just basically reiterating that I think this is very timely. And I'm particularly grateful for the manner in which you wrote it. I mean, just based on the reading. So, congrats.

I have one. [AUDIO OUT] O-G-C-I. Sorry, Aurora? OK, I'm just curious. So Exxon and Chevron joined the OGCI today. You have any hope there? And one of the priorities that oil and gas climate initiative is for them to invest in [AUDIO OUT]

Yeah, Exxon and Chevron both joined.

Yeah.

I was surprised, too.

And as you know, one of their priorities is carbon capture. I'm curious about what your thoughts are, what kind of hope we can have that they'll invest some serious money?

Well, I mean, they are putting—I mean, each company I think is committed to $10 million, maybe more. But their grouping some research. Let me generalize that to what we need. And I talk about in the book a little, you need both technology push and you need market pull. You just cannot invest enough in research to make up for what the market incentives could be. I mean, the market will be more. But I think you need both of what you have.

I think Jake's surprised. In my book, Jake and I worked with Exxon a lot. And Exxon just does not join ventures like this. In fact, they've always been proud of not joining ventures like this. So it's sort of a surprise. We'll have to talk to our colleagues on Exxon and see what their thought process was. And I'm even surprised on Chevron a little. So there must be pressure on them to do it.

So, I think it's a positive thing. But by itself, it's not going to solve the problem. It's just one small part, or maybe bigger than a small part. But it's just one part of what we need. And I think the biggest problem right now is the United States government is just really not providing leadership, but it's going backwards. So it will be interesting, this and that. It will be interesting in a couple of weeks when the IPC's special report on 1.5 degrees C works. And they're going to be talking about we've got to be over here. And we're over here today, and there's going to be this giant gap. It'll be interesting to see how people talk about it.

Thank you, Howie, and thanks for all the work you've been doing.

[APPLAUSE]

I'll be happy to sign books. I'll stick around. I'm happy to do that.

Listen to the talk:
https://soundcloud.com/mitenergy/carbon-capture-mit-press-essential-knowledge-series