Amy: Tonight's Cafe is called Climate Solutions, Renewable Energy Storage and Carbon Capture. I'd like to thank the sponsors of this evening's Science Cafe, Sigma Xi, the Scientific Research Honor Society, University of Michigan Chapter. I'd also like to thank this National Science Foundation, which has supported our speakers in various ways associated with the museum and tonight's program. Now, I'd like to invite Gus up to tell us more about Sigma Xi and then he will turn things over to Kira. Gus, thank you so much.

Gus Buchtel: Thanks, Amy. I am Gus Buchtel and I'm currently the president of our local chapter of Sigma Xi. I'm just gonna say a couple of words about Sigma Xi and then we'll get on to the more important things. Sigma Xi is the largest multi-disciplinary honor society for scientists and engineers. It was formed in 1886 back when Phi Beta Kappa would not induct scientists into the honor society. The scientists just made their own honor society called Sigma Xi. Our chapter was formed in 1903, and so we've been around a long time. We have currently more than a thousand members in the campus at all levels. The mission of the society is to enhance research, foster integrity in science and engineering, and promote the public understanding of science. It's the latter mission of promoting the public understanding of science that motivates our chapter to sponsor events like tonight's Science Cafe.

Other activities of the chapter include judging and awarding prizes at the Southeastern Michigan Science Fair and giving cash award to a science and math teacher of the year, whose teaching inspires, stimulates, and challenges students. Thanks for giving me a chance to explain Sigma Xi.

Kira Berman: Sigma Xi has sponsored two Cafes this season. They've also sponsored one that's coming in May on the Future of RNA vaccines. Many, many thanks for the dollars that make the appetizers happen, so, yes, thank you very much.

My name's Kira Berman. I am the Assistant Director for Education at the Museum of Natural History, and I organize these Science Cafes in order to give you an informal chance to hear from and talk with the researchers at the University of Michigan because I think that that can be transformative for people and their understanding of science and technology.

I want to give you a sense of what's about to happen for those of you that may not have attended a Science Cafe before. The first thing we'll do is we'll hear from our two speakers. Charles will go first and then David will go second. Then, the next thing after that is we'll let you take a break, order another beverage, and discuss what you heard at your tables. Our speakers will circulate in the room, so you'll get a chance to talk to them as well. Then, for the last half hour, we'll do a large group discussion which I will moderate, so that's the format of this evening.

Let me introduce our speakers: Charles McCrory is Associate Professor in the Department of Chemistry and the Macromolecular Science and Engineering Program at the University of Michigan. Before coming to the University of Michigan, Professor McCrory was a research scientist at the Department of Energy Innovation Hub called the Joint Center for Artificial Photosynthesis where he worked on evaluating catalyst materials for solar energy storage. At the University of Michigan, his group develops new catalysts for storing renewable energy in the form of chemical bonds like solar fuels.

David Kwabi is Assistant Professor in the Department of Mechanical Engineering at the University of Michigan where he teaches courses on energy technology and thermodynamics. He is passionate about developing technologies that will enable a low carbon climate-friendly and sustainable energy industry. His group designs and studies electric chemical devices for storing electricity, capturing carbon dioxide from the environment, desalinating water, and similar applications.

I'm so, so pleased to have these two with us. I don't want to fail to mention that these two gentlemen both have NSF research projects that have funded exhibits that are either at the museum or will soon open. Charles has what we call a pod. It's a little room in our People in the Planet exhibition. You should definitely check that out; it's mostly about batteries.

David has a research station in People in the Planet and then will soon have a research highlight station up in our nature lab. After the cafe, go to the museum, and you can play around with the exhibits and learn more. Without further ado, I'm gonna let Charles start us off.

Charles McCrory: Thanks again for inviting me and thanks for listening to me during this event. What I wanted to do with my talk is give a broad overview of types of renewable energy storage that are used and emerging and would we even need something like renewable energy storage? A lot of people here probably know these types of graphs with these types of knowledge is put up a lot. Looking at atmospheric carbon dioxide and the fact that it's increasing like the blue line suggests and it's been increasing since 1750 all the way to today, pretty rapidly since the dawn of the industrial revolution in the early 1900s. You can see that it matches very closely with CO_2 emissions, so as CO_2 emissions go up, so does the atmospheric CO_2 in the atmosphere. What we need to do, or one of the ways to mitigate increasing CO_2 is to capture it. I'm not gonna talk much about that but Professor Kwabi will.

Another way is to decrease our dependence on energy generation sources that generate CO_2 so move towards renewables and that's what the world has been doing. According to the Department of Energy, US Energy Information Administration, if you project out the growth in different sectors of energy from now until 2040 or 2050, you see that they're projecting renewables will dramatically increase. Renewables, primarily wind and solar energy, will dramatically increase compared to other energy sources over the next thirty years. If you look at, even right now about 13 percent of our energy makeup in the United States is in wind and solar energy.

This is awesome, we're getting these new energy sources that don't directly emit CO_2 and we're bringing them on. They're coming lower in cost and they're becoming cost competitive with other things like coal and natural gas. Next slide, please. The problem is that wind and solar energy are intermittent and what we mean by that is that the sun comes up, the sun goes down. If you look at energy generation from solar energy, this is just two days in August 29th and August 30th, and I think 2021, solar energy, not surprisingly turns on about 6:00 a.m. and decreases and is completely gone by midnight.

Then, again on the 30th it starts at about 6:00 a.m. and decreases at midnight, so it's intermittent. Wind energy is all over the place. Who knows when we're gonna get wind or not, right? It depends on the weather; it depends on a lot of different factors. It's not like we're firing up a coal power plant or a nuclear reactor, it doesn't give you constant, steady generation of electricity. We need a way to harness this electricity when it's generated to use it at the times when it's not being generated. Next slide, please.

It gets even worse, by the way, if you look at monthly, wind is all over the place if you look at average generation over a month. Solar also, it peaks in the summer, when you have more time, more solar sunlight, and decreases in the winter when you have less sunlight and less usable hours. Not only does it vary by day-to-day, it varies by month-to-month, so we really need long-term storage strategies. We need the ability to store energy during peak production so that we can use it during periods of dark skies and calm winds.

There are lots of different strategies that are used in the United States to store energy. Next slide, please. Probably the biggest storage, grid-scale storage solution that is used in the United States is pumped hydro storage. About 93 percent of all energy storage currently in the United Storage is pumped hydro storage. This idea that when you're generating peak electricity, you literally are taking water and pumping it uphill, from a lower reservoir to an upper reservoir.

When the electricity isn't being generated, and you want to re-harness that energy that you stored by pumping the water, you trickle it back down, it spins a turbine, generates electricity. Simple idea, it's incredibly efficient about 80 percent energy efficient, that means 80 percent of the electricity you put in to pump the water up the hill, you get back when it trickles back down. It's great if you have lots of freshwater and lots of mountains. Michigan has lots of water, we don't have any mountains here. You have to construct—or not many mountains, so you have to construct large hills or large elevation changes in order to do this.

Places like California, most of pumped hydro storage is in California. They have a freshwater problem. They can pump water up and downhill, you don't want to pump saltwater because you create salt lakes that kill everything around it that have horrible environmental costs, so you need to use freshwater. You have to have both mountains and freshwater to use this. Where you have that, it works great, places like Michigan, probably not so much.

We're looking at other ways of storing energy that could be used everywhere. Next slide, please. A great idea, batteries. If you buy a solar panel today and you put it on your roof, the company will probably try to sell you a battery pack, a lithium-ion or other intercalation battery pack that would store the energy during the generation. They work pretty well; they're ubiquitous in electronics and automotive energy industry. Everyone who has a cellphone has a lithium-ion battery in their phone right now. They work by taking—you have lithium ions—it's called lithium-ion batteries because you have lithium ions, they like to reside in what's called a cathode. It's a lithium cobalt oxide, that doesn't really matter, but the lithium is stored on that side of the battery, and it prefers to be there. It's energetically favorable to be there.

You pump in electricity and energy; you force it out of its preferred space into graphite sheets—in between graphite sheets where it really doesn't wanna be. It's really energetically unfavorable to be there, so you're forcing it—you're using energy to force it into a place it doesn't want to be, that's the storage part. You can release that energy back by letting the lithium get out of that graphite and go back to the lithium cobalt oxide cathode. It's about 90 percent energy efficient, so pumping water uphill's about 80 percent efficient, this is about 90 percent energy efficient.

Great idea, some problems: power density is always a problem; scaling it to large sizes, that's becoming more and more. You know you've got the Ford F150 Lightning being built here in Michigan—I think it's—yeah, being built here in Michigan, that's an example of scaling the size of these lithium-ion batteries even larger to run entire trucks. Cycling lifetime continues to be an issue. You wanna be able to store for decades so you have to be able to cycle these back and forth. As you cycle this back and forth, you get materials degradation, so that's an issue. Also, you're using lithium and cobalt, not the most environmentally friendly substances in the world, not the easiest to mine, and we don't have a lot of it in the United States. Most of cobalt actually comes from the Democratic Republic of Congo, which is not a place that we want to be mining our resources from.

Flow batteries are another example that can be very energy efficient. They're much more readily scalable. They're probably at a lower technology readiness level, meaning they're not employed as universal as lithium-ion batteries for a variety of reasons.

There's a lot of current research going into efficiency, powered density, cycling lifetime and if you click again I believe Professor Kwabi's gonna talk a little bit about flow batteries in addition to some other work later in the talk. He's certainly one of the experts here at Michigan working in the flow battery realm. I'm not gonna talk so much about that.

If you click again, but a different approach that we're really excited about in my lab isn't batteries, it isn't pumping water uphill, pumped hydro storage, it's storing energy in the form of chemical bonds. This idea that you can take renewable electricity and water and couple that with waste products like CO_2. CO_2 is an industrial waste product, you couple those together in a reactor to form fuels or chemical feed stocks, things like methane or methanol. Things that you can directly use in a fuel cell or directly burn if you want to, in a combustion engine, and then recycle that CO_2 constantly combust it, capture it, convert it, combust it, capture it, convert it, *et cetera*. That's the idea, so we're gonna store it in the form of chemical bonds.

The most common way of thinking about this is water electrolysis. This idea that you're gonna use water and electricity, you're gonna couple those together, and you're going to split water into hydrogen gas and oxygen gas. It's a chemical reaction taking electricity and separating water into its two constituent elements. Hydrogen, if you've heard of the hydrogen economy, hydrogen's a really good fuel source. It has some issues with storing it, and it's very light, it's hard to transport it, but it's a very efficient fuel source and it can be combusted directly or used directly in fuel cells for energy generation. This is one example of a solar fuel, taking solar or wind electricity, and converting it into a chemical fuel source.

What we work in my lab, next slide, is actually doin' something a little more complicated, taking carbon dioxide and water, combining that with electricity to generate methanol. Where methanol can be used directly as a fuel source as well. The issue in all of these reactions, well, there are lots of issues, but the issue that we focus on, on making these reactions reality, is you need catalysts to do this reaction. What a catalyst is, if it's a material or a molecule that accelerates reactions by helping break bonds and reform bonds, so it's something that helps us get across these energy barriers in these reactions by facilitating the cleavage of bonds, in the case of CO_2, breaking carbon and oxygen bonds, and then reforming bonds, creating carbon, hydrogen and hydrogen bonds to form hydrocarbons and fuels.

Next slide, so what we do in the McCrory Lab, is we design new catalysts and materials, specifically for the conversion of these wastes like carbon dioxide into useful chemicals and fuels. That's a picture of some of my students in the lab; some of 'em are present here today as well. Yeah, so that's what we do and how we approach chemistry in the McCrory Lab.

Amy: Okay. We'll go straight to David Kwabi's presentation.

David Kwabi: This is a real privilege for me to be here and to talk a little bit about my research to you all. I don't normally talk about my research to audiences like this, so this is really wonderful. You guys are—your taxpayer money funds my work so feel free to ask all the hard questions when the time comes.

Charles did a really wonderful job talking about why we're interested in storing renewable electricity. I'm gonna talk a little bit about some of the work my group does in terms of designing devices that store lots of electricity really cheaply, and also devices that can capture CO_2 from the environment, okay.

Let's go to the next slide. What I wanted to talk about—so I wanted to go back a little bit to this idea of pumped hydro and use it to motivate why we're interested in the source of devices we work on in my group. If you think about what a pump hydro plant is, it has three components, right. You have a reservoir that's really high up and then you have a reservoir that's really low, and you have a turbine in between them, the water flows downhill, and you get electricity out.

You wanna store electricity, you can pump the water uphill and it's a really simple system, really. What makes this a really fantastic way of storing energy is the fact that if you wanna store more energy, so if you wanna increase the amount of energy you store in your system, you just need a bigger reservoir and more water essentially, right. It turns out that this is really cheap, right. The bigger your system is, essentially, the cheaper your—in dollars per unit of energy you're storing, essentially, right. Turbines are really cheap and they're also really efficient, so we know how to make those and make them at the scale we need to store the electricity or store lots of electricity, really, right.

That's what pump hydro does for you. The amount of energy that you store in a system is just equal to the amount of water you can store at the high elevation, and then also the distance between high and low, really, it's just a product of those two, all right. Now, we're very much inspired by this idea of decoupling the energy and power, and essentially that's essentially what we do with flow batteries. Flow batteries are an electric chemical analog to repump hydro system instead of storing water at a high-elevation, we're actually storing electrons or electricity on molecules that store the electrons at either a high potential or a low potential.

In much the same way that you have a high-elevation and low-elevation reservoir, you have a tank—if you look on the right, you have one tank that stores electrons at a high energy and then another tank that stores electrons at a low energy. Then, if you want to either deliver or store electricity, you pump that electrolyte or the fluid in the tank into a reactor and that reactor's essentially equivalent to your turbine, okay. The analogy here then is that the height of the elevation difference in the pump hydro translates to a voltage difference in your flow cell. Then, the amount of mass or the amount of water you're storing is gonna translate to the number of molecules you can put in the tank essentially, the concentration of the molecules you can put in there. That's how the two relate to each other.

The nice thing is that if you want, again, if want to store more energy, you just increase the size of your tank. In principle, you can end up with a really cheap system if the molecules you put in the tank are cheap, okay. At the moment, people are really interested in using molecules based on vanadium, so vanadium—the v's you see there on the right are just shorthand for vanadium—if you don't know what vanadium is, that's—shouldn't be—that's no surprise because it's a very old element. It's something that exists in the earth's crust in very low concentrations and as a result, it's really expensive.

The vision that my group and a lot of groups around the world have, is to replace these expensive elements with really cheap molecules, okay. That's what we work on in my group, thinking about really cheap molecules that can store energy in these flow batteries and if you go—if we go to the next slide, I have a few examples of the source of molecules that we're interested in working with. What really excites us about these molecules is that they are, in a sense, all around us. They're known quantities so there's molecules that you can derive or that are found in things like broccoli and rhubarb. In fact in, I guess, like five, ten years ago, people called this the rhubarb battery because these molecules exist in nature, in plants and so on. Nobody's squeezing rhubarb and making batteries in my lab, but people make that connection.

There's hydroquinone, which is a acne treatment, in the middle-left panel there, and then, the red and blue, those are molecules that are used in the food and textile industry as dyes. About half of the molecules that are used as dyes in the food and textile industry, look a little bit like the yellow powder and the molecule right next to it that you see over there, okay. Then, on the bottom right, the black stuff that you see in the person's hands, that's coal tar, which is a byproduct of refining or extracting coal and we have a lot of coal tar. Turns out there's a chemical in that coal tar that you can actually make into a—or convert into a molecule that can store energy in these flow batteries. In principle, we could take a lot of the quote, unquote waste stuff from the fossil extraction business or industry and use that for renewable energy storage. That prospect is really quite exciting to us.

Here's a picture of what our experiments look like in the lab. On the left, you have a little reactor in the middle, and then you've got two, we have—I show tanks in the first slide, but these are just two little vials, right. It's all scaled down, so we can do some detailed investigations at lab scale. You got those two-colored electrolytes that are being pumped into the reactor and be pumped from the reactor into the reservoir and back again, okay. The really cool thing about these organic molecules is that sometimes they—they're strongly colored, and they often change color, so it's fun for students to see all that happening as the battery's being cycled.

On the right, I'm showing a plot of the capacity of some of the batteries that we work on as a function of time. These curves are just—represent two molecules. One molecule, the one with the black curve, we found has a really high rate of degradation so when you see—if you see the light at the slip go down, essentially that you're losing capacity as you charge and discharge your battery. This is some work I was involved in, several years ago, but what we did was we took that molecule, and we made a really small change to its structure, and we saw that we go from losing five percent capacity per day to something like five percent capacity per year, okay. By making a really small tweak to the structure of the molecule, we found that you can make a really dramatic improvement in its lifetime. We want these batteries to last a really long time; we want 'em to last for decades and so five percent per day isn't gonna cut it. You wanna be losing on the order of maybe five percent per year, maybe even less than that, okay.

This is the research we work on for energy storage and we're, in a sense, piggybacking—we present is our piggyback on the flow cell architecture and start working on CO_2 capture. Charles mentioned that we—eighty percent, roughly, of our energy use is coupled to CO_2 emissions. We need to get that number down quickly, and there's some concern that we might not be able to do so in time to avoid many of the most disastrous effects of climate change. People are really interested in figuring out ways to capture CO_2 from the environment, from the atmosphere, and so on.

We're interested in taking many of these molecules and using them for CO_2 capture. The way this works is that it turns out that many of the molecules we use in our flow batteries for storage, when you push an electron onto it, it naturally removes a proton or a halogen ion from water and so it changes the pH of your solution. I'm showing an example of a reaction up there in the middle-left portion of the slide. You can see that you're—you're going from left to right; you're moving a proton. You go from right to left; you dump a proton. What happens where you remove a proton from water is that it becomes alkaline, it becomes basic, and it can actually capture CO_2. You can capture CO_2 in solution that way, okay. Left to right, you capture CO_2; right to left, you can bubble out—you go the other way, you can bubble out CO_2. What we're doing now with our beer glasses. You're bubbling out the CO_2 that's dissolved in there. In principle, you can release that CO_2 and store it somewhere else, okay.

We have been working on applying this strategy to capturing CO_2 from air, but it turns out that's really hard because the concentration of CO_2 in air is very low. It's about one CO_2 molecule for every twenty-five hundred molecules of air, so that's challenging. What we've instead decided to do is to look at capturing CO_2 from seawater because it turns out that about a quarter of the CO_2 we pump into the atmosphere ends up in the ocean and it actually ends up being more concentrated in the ocean.

You have about a hundred times more CO_2 per volume in the ocean than in the air. That's another application that we've started looking at quite seriously. You can't dissolve organic molecules in the ocean. That's not okay, it's illegal but what we've decided to do is take these molecules and actually stick them onto solid surfaces, essentially immobilize them, and then put that in seawater and try to change the pH of seawater to release CO_2 and then store it somewhere else, okay.

On the top shows an example of the source of substrates or materials we work with, actually. The white stuff you see there is actually wool felt, very much like the wool you would wear. You can take that wool felt and with some really fancy chemistry—and we have collaborators who help us do this—you can coat that wool felt with the molecule that does the proton storage, and you get the black stuff on the right. You can see a very zoomed in view of the fibers of the felt. You can see that it really well coated with the molecule. You get this nice film on top of it when you go to that or that fancy chemistry. We've shown that you can use this. You can actually remove CO_2 from seawater and there's research ongoing towards demonstrating that you can do it for very low cost, okay.

This is a little bit of an introduction to my research. We're doing a bunch of other things with showing that you can, in principle, use light as a way of driving CO_2 out from seawater. I have a postdoc here who you can talk to about that. Raise your hand, postdoc, there you go. Pester him if you wanna learn more about that particular strategy. Moving forward, I just wanted to end with this question of what would implementation of these systems actually look like? Charles mentioned flow batteries aren't everywhere now because they're very much—they very much need a lot of research and the fundamental understanding. We can imagine what they might look like because there's some demonstration plants that are coming online in certain parts of the world. On the top left, that's a flow battery plant in Dalian, China which is gonna be rated for 800 megawatts.

Just to give you a sense of perspective—or you can actually see how big it is from everything around it, so I wonder if like a city block or so. It's 800 megawatts. To give you a sense for what that number means, it's if you take just a standard coal plant and run it for an hour, that's all the energy you're probly gonna get. This battery plant can store all the energy just to give you a sense of perspective and it's really quite big. By the way, those little black things you see on the roof there, those are solar panels. The goal is that the solar panels capture electricity, and you store it in the flow battery farm, essentially, and then you can release that energy when it's needed.

There are various sorts of visual representations of what flow battery installations might look like from Lockheed Martin. I'm not gonna comment too much on that but you can take a look at that to get a sense for what your future might look like driving around the neighborhood looking at flow batteries. Then, with regard to CO_2 capture, what we're gonna do to CO_2, that's another question that people often bring up and something we can certainly discuss in detail as we move along here at today's program. One thing you can do is store it. Another thing you can do is give it to Charles so he could turn it into a fuel or some sort of chemical. There are lots of options and there's lots of policy discussion and just a lot of thought that has to go into what we end up doing with it, which I'm happy to engage in a discussion with you all about. Thank you for the opportunity to present my work here.

[Applause]

Amy: Awesome. I'm so excited by the interesting questions and discussions that I heard as I walked around the room. This is a really compelling topic. This next part is a group discussion—with a question. Okay, I'm gonna go back here and then you're up next.

Audience member 1: Thanks so much for this presentation. I really appreciate your sharing your work that you're doing here. My question has to do with the concept of exploiting the work that humanity has already done with our land on our resources and the extent to which you see the existing landfills as an opportunity to mine for both of what you are working on.

Amy: To repeat the question, can existing landfills and other byproducts of our industrial activity be mined for the kinds of things that you guys work on?

David Kwabi: Yeah, that's a tough question. I tried to address that a little bit when I mentioned coal tar as a potential feedstock for molecules that you can—that we can use to store energy in flow batteries. In general, this is a question that many researchers consider in study about their work. The question is can you use or leverage commonly available feedstocks or materials that are already present in everyday life for the technology that you wanna build. To some extent, that's possible with flow batteries, it would depend on precisely the sort of molecule you want to make. If that molecule has a highly abundant natural feedstock, then in principle you could do it.

This is obviously a very live question and one that many people are considering. The other thing I mentioned with regard to textiles is that the hope there is we can leverage all the efficiency and economies of scale and sustainable practices that are developing in the textile industry. If we're making electrodes from those textiles, then we can translate that to what we do in energy research. Maybe that's not a complete answer to your question, but it's one that many people do consider and in some cases that is possible to use waste products as a *[unintelligible 00:34:11].*

Gus Buchtel: I would just add in, in the realm of catalysis thinking about solar energy conversion to fuels, or even in intercalation batteries, a lot of the key components are metallic in nature, right? They're copper, manganese, cobalt, different transition metals. Yeah, we throw a lot of that away. A lot of that is our landfill. I think it's a cost issue. Is there a financial benefit to mining that from landfills or societal benefit that can be translated into a financial benefit for mining it from landfills versus from mining it directly from mines in the ground.

I think, especially for things like lithium and cobalt, recycling of those have become very important because we know that our lithium and cobalt sources aren't probably very sustainable and aren't mined in very good ways and so—and from friendly countries. We're thinking about how to recycle and how to reuse existing waste in that way. For other metals like copper, manganese or iron especially, those are much more abundant so there's a little less of that. As costs rise, I think we'll think more and more about active recycling and trying to look through old sources and reuse them.

Amy: Okay. Next, I think we had a question over here.

Audience member 2: Hello. Can you hear me? Got it? Okay. Thanks again for your talk tonight. It's super timely given the IPCC report, we've talked about a little bit—

David Kwabi: Yeah.

Audience member 2: - at our table. I'll get to it. Given that you just mentioned Charles and David the financial aspects or maybe the lack of financial aspects of some of these technologies, the fact that some of these won't be profitable for some time, what do you think the likelihood is that the US is gonna get it together in a reasonable timeframe that makes some of this stuff, the rest of some of our lives reasonable? Sorry, I know it's not uplifting.

Amy: No, that's okay. It's always great to ask researchers what they think about politics.

[Laughter]

Gus Buchtel: I'll try to avoid politics on this, but I will say that I think the US government has recognized that there's an issue with renewable, sustainable in energy, and climate change. I think that's a realization Department of Defense, Department of Energy, the National Science Foundation, they all recognize this. Department of Energy recently released earth—what they call Earthshots, which are these big themes of ongoing research. One of them is this idea of conversion and making—they talk about hydrogen but it's a broader sense of making renewable fuels or capturing CO_2, somehow addressing the climate issue. National Science Foundation also has several centers that they're developing along these realms.

I think it's something that the federal government has been interested in. Industries are starting to become more interested in it as well. Many oil companies have research in renewables because they see it as an emerging market. It's all about making sure that there's financial incentives but I don't think it's possible without government support because it's not a short-term financial benefit. No one knows the timescale to making it a financially accessible technology.

David Kwabi: Yeah, I don't have much to add to that, but I will say that I—I think it's important to take note of the fact that there's already quite a bit of momentum around these technologies and I think it's easy to lose sight of that in the fact that from the IPCC reports and so on. There's a big problem with climate, maintaining the climate at reasonable levels but there's already a lot of momentum with renewable technologies. Solar energy, solar electricity is really, really cheap right now, as is wind. The cost is at par with fossil fuel power or even, even lower in a lotta cases.

There's a huge economic incentive for figuring out how we can solve the storage problem. Lots of really interesting ideas that are out there that people are working on. I have this plant from Dalian, China. There are some in the US as well. There's flow battery companies that are starting up here in this country. You probably don't hear a lot about them because there's a lot of research going on and a lotta planning going on. There's momentum, so it's not all doom and gloom. *[Laughter]*

Amy: I will say, "Thank you very much." I will say that when you were talking about the worst effects of climate change, I thought maybe you were talking having to cancel Science Cafes, but maybe not.

[Laughter]

Audience member 3: Thanks for being here. Recently, there was a pool of even democrats in the United States and way less than 10 percent felt that climate change was a major priority for our country. What do you think that researchers and scientists, like you, and ordinary people like the rest of us, what can we do to increase the consciousness of the threat and the urgency of the situation? Not only in terms of just the whole energy thing but global population and those things go hand in hand.

David Kwabi: Okay, well, so I'll take the first part and then I'll let Charles take the second part about population.

[Laughter]

David Kwabi: I'll say coming—I think events like this are wonderful because, like I said at the beginning of my presentation, this is taxpayer money driving the work we do and in a sense we are accountable to you all for how we use that money. I think events like this are a fantastic way to start. I don't know the research about exactly who is concerned about climate change and to what extent. My understanding has always been that people understand, at least for now, increasingly understand that this is a real issue and that we need to do something about the way we've coupled our energy use to CO_2 emissions. I think the biggest set of questions come up when we start thinking what exactly to do given the many options that are on the table. That's the case for storing renewable energy but it's very much the case if we want to think about carbon capture, which touches off a whole nother set of—opens up a whole nother can of worms. I think in a nutshell, public exposure to and accountability in events like this, and perhaps other events of this nature, would go a long way to raising more awareness, but yeah, population growth?

[Laughter]

Gus Buchtel: I'll just say one more thing on what David was commenting on. I think that energy literacy and scientific literacy is definitely a place for improvement in the United States. I think that it is incumbent upon active scientists either in academia, also in industry, but to communicate more with the public so that there is more public awareness. I'll note that the University of Michigan, National History Museum has a Science Communications Fellows program that actually trains graduate students and postdocs and effective scientific communication to the general public.

I know my lab has taken a lot of advantage of that. I think that that has perhaps been forgotten for the past 10 years or so, and it's starting to become—scientists are starting to realize more and more how important it is to engage with the general nonscientific public in order to increase awareness in literacy about these issues. The health community has done that to a large extent. They're very good at that. The non-health-science community has really struggled in that area, and I think that's really important.

In terms of the increasing need for energy, the increasing CO_2, it's all tied to population growth, absolutely. Population growth also increases land use, which leaves less land for things like solar arrays and wind farms because you need that arable land for crop production to feed the growing populations, and so that's a real concern. How do you produce energy where you can, and store it or transmit it to where it's needed, and those two things are often not in the same location and how do you do it cheaply enough that it's accessible to everyone and not just rich developed nations? I think that that's a real challenge that's being struggled with.

There's a lot of talk about distributed energy. I don't know how practical or impractical that is but the idea of doing smaller scale energy production with local storage, so you don't have to have the capital investment of large plants. There are issues with costs of those compared to larger plants. There's a reason everyone builds massive plants, they're cheaper to run than when you have distributed. I think that that's something that scientists and engineers are very conscious about and there's a whole area of research and energy policy that focuses just on how to get energy where it's needed as populations grow, and predicting those population growths, and the energy distribution networks that are needed. Some of that's happening at the University of Michigan. Some of it's happening at the Department of Energy at National Labs but there is research in exactly that because it's an incredibly important area of research.

Amy: Thank you so much, that's really important.

David Kwabi: I'll just mention one more quick thing, with regard to drumming up excitement and awareness and so on, and that's—I think if it's possible—and this is just my personal opinion, if it's possible to reframe this as an exciting challenge, and not just as a burden to be shouldered and solved and managed, I think that could drum up a lot of excitement. In much the same way, perhaps, that the space race drummed up excitement for science back in the day. If we can think of this, not just as something we need to solve to survive, which is—it is the case, but also something that's—presents exciting opportunities for science and research. I think that could go part of the way to helping people get involved.

Amy: Awesome. Thank you.

Audience member 4: Okay. Now, as far as alternate energy sources go—one could already guess are fossil fuels, one that has always been an advocate for but also prolly one of the more controversial sources, is nuclear energy and nuclear power. I'm curious to know where you two guys stand on this as an alternate energy source.

Gus Buchtel: I'm a big fan of a large portfolio of energy sources. I think that nuclear will probably play a role in that portfolio of emerging energy, that's my guess. I know that in Europe, in particular, nuclear energy has been a big part of their energy portfolio, and they recycle nuclear waste much more efficiently and better than we do in the United States right now. My guess is that nuclear will be a part of it, but I don't think given the cost of nuclear plants, how difficult they are to build and maintain, and where uranium is located—minable usable uranium is located, I'm not sure that uranium power plants are going—they're gonna be a component, but we're not gonna be 100 percent nuclear country; I don't think that we possibly could be. I think it's gonna be part of the portfolio but it's not—it's not the only answer. I don't think there is one only answer. I think it's gonna be a broad distribution of energy sources just to meet the growing need in our country, and then globally.

Audience member 4: All right and the second thing, regarding a nuclear energy, you probably know, one of the biggest controversies is because of the radioactive wastes it leaves behind. Do you think it's possible that maybe we could turn that waste into something—into a fuel source of itself like what you talked about with some of the alternates, the sources you discussed?

David Kwabi: Yeah, so, I agree with Charles, that's why I didn't have to add anything. I think nuclear is going to be part of the solution as well. With regard to fuel efficiency and potentially using—I know there's lots—there's a new engineer in the room who can correct me if I go wrong on the facts here, but there are other ways of using nuclear fuel beyond the once-through cycle that we currently deploy. You get your uranium, you enrich it, it goes once through a power plant, and then you put it in the spent pool or just leave it out, wherever it is.

There are ideas to use things like breeder reactors for example, which essentially make more fuel as the nuclear plant goes along. You start with uranium 238, and then you actually make that—you enrich your uranium 235, which is the fissile part, and then you can make more fuel as the reactor operates. You make plutonium for example, which causes issues with proliferation because of nuclear weapons and so on. In principle, you can extend the lifetime of your nuclear fuel by using a breeder reactor. In fact, the first breeder reactor in the states was in Michigan, actually, Fermi 1, which had a—there was a little accident, I think, in the '70s.

[Laughter]

David Kwabi: It was built, and it's there, in principle maybe that—these ideas could come back to the fore.

Audience member 5: I asked this question of you a little bit before, but I'm really interested in this technology of the flow batteries, and to talk a little bit more about the pros and cons of the development and how close you are to actually implementing the technology in the United States.

David Kwabi: Okay, so pros and cons of flow batteries, so the main pro is the coupling of the energy and the power. The fact that if you wanna store more energy, you increase the size of your tank, or you can increase the concentration of the molecules in there. You don't have to increase the size of the reactor so there's a cost advantage. The con is now you have to think about the molecule you put in there and because you're storing the molecule in a solution, you can't store as much energy in the same space as a typical lithium-ion battery. These things are gonna be large, I suppose, is a con. You have to start thinking about land use issues, and so on, and so forth.

That said, there's a variety of chemistries that people are playing with. There's companies that are starting to work on organic molecules and metal-organic complexes and various sorts of chemistries that I can talk in more detail about. I don't know how far away they are from practical implementation. A lot of this is just gonna be driven by the economics and the price of these molecules essentially. I'm personally optimistic that they're gonna make a dent—that they're gonna play a role in the renewable low carbon energy future but I can't put a precise date to it, unfortunately.

Audience member 6: Hello, I wanted to ask regarding the flow batteries in—when these molecules that we use, they lose their capacity, what is the current standing on, do we recycle these molecules? What is the—what do we do with these degradation products?

David Kwabi: That's a good question, so the—it depends on the timescale of this loss—of the formation of these degradation products. If this happens on a very, very long timescale, and you're losing about 20 percent of the capacity over, I don't know, 20 or 30 years, so maybe it's not a big deal. In 20 or 30 years, maybe the project would have ended, and you recycle, you take the whole thing apart. If you're losing capacity on a faster timescale then you have to figure out—well, for one thing, it's probly not gonna be economic to actually set this up as a battery installation.

People are looking into ways to essentially regenerate molecules that have decomposed using a variety of electric chemical and chemical strategies. This comes back to the point Charles made earlier about recycling. It's just gonna be really important for us to figure out how not just to—how we build up these systems and how to reuse their components and keep going. Yeah, good question.

Amy: Before we go to our last two questions, I want to just remind you that on your table there are little blue evaluation forms for you to suggest topics and give feedback about tonight's Cafe. NSF, which partially funds this Cafe, would love it if I had a really good feedback report for them with lots of data, so I encourage you to fill out the little forms. There are little yellow pencils—notice the maze and blue theme—next to the little blue forms. With that, I'm gonna go to our second to last question, and which is—

Audience member 7: Hi, you've both mentioned the use of waste products or byproducts from fossil fuel production being used as a feedstock, are you concerned that this could be used to extend the lifetime of fossil fuel plants that might otherwise be shut down?

Gus Buchtel: I don't think fossil fuel plants need an excuse to extend their lifetime. I think fossil fuels are gonna be with us for a while. I think that one of the things—so often, when we talk about capture and conversion, we talk about CO_2 at or capture, in general, we talk about CO_2 coming from these wastes 'cause that's where it's generated. Fossil fuel pure plants but also industrial processes that use heat and energy and fossil fuels to do conversions.

I think that—sorry, I'm distracted a little bit—I think that—I don't think that it's going to be used as an excuse to continue them. I think that we're gonna continue burning fossil fuels. I mean as you saw the projections are well into after 2050. Even if it's a smaller percentage of our energy use, I think a good goal would be to maybe come up with renewable energy strategies that were not building more fossil fuel plants and that we can start turning on renewables instead of building more fossil fuels.

Obviously, the best idea would be to do direct air capture where you're taking CO_2 just directly from the air, capturing it, concentrating it, and then either storing it long-term or converting it into something else, but that's a much lower technology readiness level than taking it from what we call flue gas, which is the output from a fossil fuel plant.

Audience member 7: Okay.

Amy: Last question.

Audience member 7: Also from the McCrory Lab. *[Laughter]* I was wondering what you think about the general efforts into scaling the, I guess, the large-scale efforts into CO_2 or general energy related things, and if there's—if you think there should be more funding and, or research into the steps of long-scaling along the way to get to these huge—maybe like a flow battery at the scale of the—in China and stuff like that?

David Kwabi: Your question is specifically about carbon capture, right?

Audience member 7: I mean just, generally, in energy research—

David Kwabi: Research or scaling, yeah.

Audience member 7: - compared to our lab or a research lab and then going all the way—

David Kwabi: Right.

Audience member 7: - to the—to this kind of scale.

David Kwabi: Yeah, so there are plenty of opportunity announcements precisely around this question is—the goal would be—so you would read the announcement, and it would be something like demonstrate to us that you can capture 100 tons of CO_2 in this amount of time, right? Calls like this come out every once in a while and you know, I would look at that and say, "I can't do that with my tiny little flow battery." I think here's a lot of interest and recognition from the Department of Energy and other government agencies that we need research not just at the fundamental scale but also along the pathway from fundamental R&D to practical implementation and there's a lot of support for that. We have a lotta ground to cover very quickly, but at least from what I've seen so far, there's recognition that we need help along all these steps.

Gus Buchtel: Yeah, I think on the scaling issue this is also a place where industrial partnerships can play an important role. Industrial chemical companies know how to scale processes. They have people that work in this area. I think finding these academic and industrial collaborations is an important step that is used, to some extent, but maybe underutilized in this area of trying to take things from a lab scale, from the two vials, to a more commercially viable scale.

Those are also important because in industry, things that sometimes we work on in the lab that we think are really interesting science or engineering problems, they've already solved that, or they say everything you're doing is too expensive, think about it again. I think having that sort of feedback is really crucial when you're thinking about taking something from a fundamental science to something that could actually be practically implemented.

Amy: Awesome. Thank you so much for being here. What a captivating talk.

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