

THERMOCHEMICAL CONVERSION OF BIOMASS

Professor: George Philippidis, MFA, Guest Speaker: John Kuhn, Ph.D.

Thank you. Good evening, everybody. So I commend you guys all for being here in the evening. I'm getting tired. I taught 86 undergrads at 11:00 AM, so they're probably long gone by now. But I'm glad to have this invitation. It's fun to talk about research. I really like doing research and conducting research.

I think it's good, because maybe someday, we'll have a good breakthrough and make a big impact in life. But also, it's a great training for students to be able to get that. And then, as they go to industry or their own companies or whatever they want to do, they're able to do that. So I appreciate having this chance this evening to talk about this.

I did put a few introductory slides. And some of them may look similar to what you just said, so I may go through those rather quickly. And I just wanted to add a couple other comments before I started, just that I think that this program you guys have here is very good, and you guys all have an interest in this topic.

I think that's really good to get other people studying on biofuels, rather than just engineers. So there's a lot of different aspects to it. And we always talk with our students that they need to be able to talk to the non-engineers, right?

So you guys are also making the effort on this end to talk to the engineers, I can tell. So it's also the engineers need to make the effort to talk back. So hopefully, there's medium ground there than we have here.

I'll talk about a few different things. And some of them-- I'm kind of optimistic, but sometimes I get pessimistic. Some of these stats I may show may look pessimistic, but that just means we have a bigger problem to solve. So that may come across, so I want to mention that now. So we have a lot of room for improvement.

The best is hopefully yet to come in all these technology areas. You saw that in the last little bit of the lecture. I saw the last twenty minutes of lecture, where things are proposed, they look reasonable, but they really need to get to the next step. And some of the other things are further away that I may touch on at the end.

I just want to point out that I work with a couple different people. Two faculty members are a department that have done some of this. And then, you guys-- I saw before you came today, you guys had a reading report from NREL. So you guys have seen a lot of NREL stuff, especially with ethanol synthesis.

This is a friend of mine. I'll show a little bit of work I've done with him in the near future-- or in the recent past, I should say, and I'll present it.

My students say-- I showed them this slide, and they said that it was not good that I put approximately 10 students, because I didn't count how many students' data are contributing to this. And they said you guys would think I didn't know how many students were in my group, if I put that. But I have a picture of them, so we can count them, if necessary.

But this is the outline I put together. I have a short overview on thermochemical biomass. That whole part will be similar to what you guys just saw. My research is mainly on the gasification routes, what you were just touching on.

So two different case studies. I've going to talk one, about real biomass gasification, oak gasification, which is with NREL. And then another one, where we're basically using a landfill as a reactor, almost like a bioreactor to make methane and carbon dioxide, and then converting that landfill gas that's coming.

And we had some entrepreneurial efforts with a very student-oriented student [INAUDIBLE], which it's called Trash2Cash Energy. So I have a disclosure that I'm involved with that company. I'm going to present some of that here today. So I think that for engineers and for you guys, as well, the entrepreneurial efforts and training that are available.

We have a good school of entrepreneurship here, all great things, too, for future efforts. And it's good for the students. I've got to learn these terms I still struggle with in the business aspect that are very important to bring on investors, which are important. the money has to start somewhere from something.

Another area I was asked to touch on Professor Philippidis on future sustainable production. So something I'm getting more into is solar fuels. I don't think that's exactly in the realm of this class, but I have a little bit of information at the end about some things.

So basically, instead of-- you talked about algae, I'm sure, at some point, and using algae for the CO₂. But if we try to use the CO₂ directly in thermochemical routes, if that's possible. So that's what the solar fuel is. So I have a little bit of that.

He may not remember in the first email he sent me for the thing. He asked me to talk for an hour. So I started putting it together for an hour. And then later, and then he said a half hour. And I started deleting things. I never seemed to remove enough to make me think I'd get through this in a half-hour. So you guys need to cut me off when I run out.

But I like this review paper a lot It's the biomass conversion from the catalyst standpoint. So I wanted to put this here. So it's about eight years old, but it's a good overview of all these different processes involved or the different routes involved with biomass conversion.

So it incorporates some of the chemical and biochemical-- I'm sorry, thermochemical, biochemical routes. It has diesel, biodiesel produced in there. So it has a lot of these different aspects in there. So you guys have seen this before, and you guys probably have talked about all these challenges that we've come up, when people talk about biomass conversion over on the right.

So there's some food versus fuel reality with ethanol, for example. But it's also just some perception. If it's biomass ethanol, you guys have talked about that. And I know you've talked about the second point there, the variability and dissimilarity in biomass. You may not get the same thing. And you talked about water management towards the end.

And the one we'll focus on somewhat here is the stoichiometric challenge, the fact that you're starting with something that's one carbon, one hydrogen and one oxygen. And you want to get something that's around CH_2 , so you have to get rid of all that oxygen and add in a lot of hydrogen.

And then, the last two points are logistics. And you guys also just talked about economy of scale. So again, I don't need to go into much detail on these right now.

So in terms of the conversion, my experience is primarily this top route. So I just wanted to mention this in case here. And I'm going to talk a little bit about ethanol, then maybe about some alkanes and hydrogen, as well, here. So we have a few different processes.

So even once you talk about the different processes that are available, you also have to say what product do you want. You guys just looked at ethanol at \$2.00 a gallon. There's also hearing people propose a hydrogen economy, the methanol economy, sticking with the alkane economy, which we have the current infrastructure for for the delivery of that.

So there's also a lot of different adaptations of that. So I guess the two examples I'll talk about are alcohol synthesis and the alkanes today.

So here's my group, currently. This is from a conference we were at the other week. And these are the three different areas our group does research in. So I think they're all important, but today, we're talking primarily about this, how to make fuel and chemicals in the most sustainable way possible. And a number of these students have pictures shown later for various aspects of what we're working on.

So I want to take one slide and do an overview of catalysis. So even though I have those three different application areas, like the fundamental bases in the field of catalysis. So a catalyst is very important to participate in the reaction, but does not participate in the overall stoichiometry of the reaction. So you guys may have touched that in a previous class in here.

So an example, you might have some sort of active site here. It reacts with-- species A absorbs on that for a solid catalyst. It goes around. It reacts with other species, has a different product. This

could desorb and go back to the gas or liquid phase. It could react again to a different one, or to a final product.

So we have three different products could form from this simple case. And each one of these little circles to the largest circle are all different catalytic cycles, where we lose-- where we have different products formed. We have the whole catalytic cycle complete. So if you add up all the way around the circle, you don't have the catalyst participating in the reaction.

And most importantly, this comes out with the selectivity. so all these are Gibbs free energy. So this is the amount of energy it takes to have the reaction take place to different products. And this graph here shows if you want to make a selective product. This a hypothetical case.

But we select one case over another case. So 0 to 1 on this axis. The two products, if you're here in the middle to go to the left or the right, this is the difference in overcoming those barriers. So these barriers are the function of which catalyst you use, as well. It's like the temperature and pressure of everything.

It doesn't take-- the whole thing is six kcals per mole on the x-axis. So it's a very small difference to go 100% selectivity to one product to another product. So there's a lot of fine tuning that can take place in the catalyst and the reaction properties-- the temperature and pressure, primarily-- to make this happen here. So we have a lot of tuning we can do to get things we want to happen.

And there's some phase terminology in this. So I do everything in heterogeneous catalysis. It usually means I have solid materials in a gas. Most of the stuff today I'm talking about is gas phase, but liquid phase. So there's also the homogeneous catalysis you guys talked about last class, which I know very little about it. He could quiz me on that, and I'd fail his exam.

And we had some funding number from a number of sources for this. The ones that are underlined are for that. So I'm going to talk about a couple of these down here that are entrepreneurial efforts with the Trash2Cash Energy. And then, this Department of NREL subcontract a little bit here.

Have you talked about the billion-ton update in this class? So you guys know all that. I can skip that slide, right? So we have a big challenge there, right? 130 sites that are all processing all these, and there's none of them currently. So there's a big challenge with that.

My contribution to this area has been in the gas cleanup and conditioning. So I noticed it's good he's shown you everything else except for that, and said it's complicated. So I'm going to try to talk about that here. So that worked out well. You can see it's important, because it's right in the middle of the slide.

So you talked about all these things here. So this is a high-temperature endothermic, a low-temperature exothermic. And there's this problem here in the middle. And he had some on the top of one of those slides, he had tar reforming somewhere. So that's one way people did it.

Before people did tar reforming, they did lower-temperature separation. So you were trying to go from a high temperature to a lower temperature, back up to a 220 Celsius, approximately. So you can see there's some process inefficiencies there. So the way people have done this more recently is try to do a reforming, which I have some of the reactions spelled out on the next slide.

So we've contributed in this. Some of my Ph.D. dissertation was on that topic, as well. So if you look very carefully at his slide, somewhere it said olivine and dolomite, maybe. So I did some research on olivine catalysts for tar reforming.

And you also see he had tars and benzenes in there as some of the components in that really big graph with all those compositions. So we're talking about those species here, and so we mentioned that.

And this is probably also something you talked about. This is ethanol prices as a function of technology. And a key part here is this tealish color in all these cases is the gas cleanup. So a significant part of all the cost with everything is doing this gas cleanup.

And so we're trying to do methane in tar reforming catalysts. So I didn't-- I'll talk about why methane reforming is also important for that. And this was an NREL study, and this may be the same one he was looking at. Or maybe a different year, because this is from, I think, 2005 or 2007.

But there's some values. So I may show some reaction data later. So these values are important for how they do the metrics for comparison.

These are from 2011.

2011, OK.

So this is much simpler than that big diagram case. But this work was in collaboration with NREL. and so this was taken from white oak they were using for that. So this is on a nitrogen-free basis. You can see a lot of the things you just talked about in the class.

You want this hydrogen to CO ratio to be 2 to 1. It's usually around 1.5 or less. And the biomass going in is around 1 to 1, so there's some char and things that form like that, that give you a little bit of an advantage to get the hydrogen to CO ratio higher. But you still want it higher, and you have all these other species here. So there ends up being a significant amount of methane forming.

So you can see we have a problem there. We have a lot of our hydrogen locked up in methane. And then, we also want to get the higher hydrogen to CO ratio, so that's why it's good to have methane reforming take place. So I have those reactions read out later. But you can react methane with steam to get three hydrogens per one carbon monoxide. So that helps us raise this 2 to 1 ratio.

The other part of this is, this is a well-known poison for catalysts. So sulfur really sticks strongly to things, even at this. You can see it's the lowest concentration in the parts per million of all those species there.

But even at that level, that's a significant amount. It needs to be about almost less than 10 parts per million for it not to be a strong factor on a lot of catalysts. So this is going to end up being important in some of our catalyst research.

And then, all these other species that are even at lower concentrations typically are these problem children, where if you do the temperature and pressure too low, you have to take the low temperature and pressure to get these to condense out to separate them.

If you don't do that, there might be a cold spot somewhere. You have condensation or clogging. And some of these are specifically challenging, because naphthalene at atmospheric pressure ends up going all the way to being a solid. So there could be a lot of problems if you have a solid forming in a flow process.

So these are why some of those end up being very expensive to remove, because you have that. So these are the types of concentrations we're looking at, where we want to convert methane at the 10% approximate level, and all of these things at the 100 part per million level. Let me show that.

So here, I mentioned a few times, we were trying to do reforming or studying the reforming process. So in itself, studying these reactions here, especially these first two reactions in the presence of sulfur, is a challenge. There's a catalytic challenge.

So there's sometimes people study sulfur-based materials. Those are really good when you're at very high concentrations of sulfur. So when you try to get sulfur out of petroleum in the processing, they usually might be 3% sulfur, so you use sulfide materials.

If you're at less than 10 part per million, you could use metals, like nickel. Not sulfide, just metallic nickel and things like that. But when you're in that intermediate area and neither one's stable, you either lose sulfur from the sulfur-based materials, or you're adding sulfur and poisoning the other one. So it ends up being where a lot of the biomass ends up being at that 30 to 50 part per million range, which is a problem.

A friend of mine actually started a company where he's trying to develop and study sulfur catalysts in that 50 part per million range, develop materials that are stable in that. And that was something I thought was very interesting from that. But we're trying to do these reactions where we have all of the different hydrocarbons and converting them.

Just to show we have a catalyst, this is what NREL was using for this catalyst. They were studying the catalyst in a fluidizable bed. So the catalyst is moving around rather than stationary. So there's two different ways people study things. So they had to pick a very strong material.

So that's what this AD90 is actually made by CoorsTek, the same people that make Coors beers in Colorado. And they make ceramics, so they make this a very strong material. And then, they add some of these catalytic components. So the nickel's the active phase, and some of these are promoters that either help nickel not deactivate or help nickel not grow to really large particles.

So I didn't mention that in the catalysis part. But solid catalysts, heterogeneous catalysts are surface area-based. So if you take something very small, that has more surface area. And if you don't want it to grow to be really big, because you take 10 of these or 100 of these and you make one big thing, you lost 99% of your surface area.

So some of these help stabilize the nickel from growing. So we don't need to go into the details of this here.

So we talk about catalyst research, we usually are taking it, scaling up. So as you guys think about the techno-economic studies that were just discussed. We want to take something small.

So in my lab, I have some pictures later. This is that NREL. We usually go a few different scales. You usually want to scale up things about a factor of 100 in time. If you go a factor of 100,000 or something, then you don't what things are going to happen, exactly.

So NREL has a nice test set up for the thermochemical cycling, so where it's on the order of something small over here, on the order of one gram, going up to 10 grams. I don't have the picture showing going up to 100 kilograms. So this is the data. I'm going to show a little bit of data where it's taken from this larger facility here in the next slide.

So this is the test they did. And I'll show you when I became involved in the project. So we have the conversion of these different species. And all of these are based off of the [INAUDIBLE] gas. So methane around 10%. these are at the part per million range, and we want to convert as much of this as possible.

So when we convert these, we're primarily making hydrogen and CO. Especially for methane, there's not going to be other side products that are gas-phase. And you can see all these lines are discontinuous. So I want to explain what that is. But if you just look at the lines across, these peak lines, you can see all of these are decreasing.

So methane is pretty stable, so it ends up being the hardest one to convert. Plus, it's at higher concentration. Benzene is these blue ones. So there, you can't even tell. It's 100% conversion all the time until you start getting out here. Repeated use of heavy tars are the easiest to reform. They're at 100 conversion all the time.

All these discontinuous things is when the conversion of a species reached some critical level that I had mentioned back there. They had to stop the reaction. So methane was 50%. And you see later

on, they let it run a little bit longer, but they stopped it. And they said they wanted to regenerate the catalyst at this point in time.

So if we have some data later, it's going to be post-reaction. They oxidized it in the presence of oxygen steam, to try to burn off any carbon that formed from the hydrocarbons, as well as any sulfur might come off as sulfates, and is re-reduced back like it was reduced at the beginning. And that's what all these points all the way along here.

So they took 30 samples out, and they were trying to characterize it. And I can show one more slide today before I tell how I came up involved with this project. So they were trying to figure out what was causing all this deactivation. So one idea was it was the sulfur composed in there. And they did an experiment like this.

The only important part of this is-- this is the regeneration step. They're heating this in wet-- in air that has hydrogen in it, I should say, not wet air, hydrogen-air mixture. And you can see the hydrogen sulfide's coming off. So they were able to know they had hydrogen sulfide in the catalytic material that they were presuming would be a poison.

But when they tried to look at this like some sort of characterization method. So if you look at things with x-rays or with visible light, you can characterize what's on the surface. They couldn't find sulfur by any ways that they were doing.

I had some experience with facilities at National Labs, and we will be able to do some experiments with this. This is a paper we published with them. So this is just to go through quickly that we do some of the research here to understand the basics. So there's going to be peaks here that related to different types of sulfur. You can see in the top where they're labeled.

So this is the freshly-reduced catalyst. There's no sulfur there. That's good, right? And then we start-- this was the first time they were able to see sulfur on the surface of the catalyst. You can see there's some sulfides and some sulfates. And they were generated. They were hoping this would go back to flat, right? But it didn't.

When they oxidized it, they changed the sulfides to sulfates. So the intensity of these aren't necessarily important, because the units aren't on this axis, but just that they're there or not. They were hoping that would be nothing. And they repeated this a number of times.

And they kept repeating back-- they were switching back between these sulfides and sulfates. So when they were regenerating the catalysts, they were just moving the sulfur around the surface. And then, it was going back. It wasn't leaving, so that's why we were able to propose some mechanisms based off this data that they weren't able to do before. So that's the research component.

And this is a friend of mine. He's a very interesting guy. I could tell you some stories for him. But I learned an important lesson from him from doing this. This was all done all night, all weekend at some National Labs. I can't remember if this data was taken from near Stanford or near Argon.

But he was a pretty devout Christian guy, and we happened to be there over all Easter weekend. And he was very upset by it, and he wanted to go to church the next morning. I went with him, and we went to McDonald's for brunch. And he was looking around.

If you ever go to McDonald's on brunch on Easter, there's a lot of people that can't afford better food than that. And it's not being mean to them, but that's where they went for their Easter brunch. And he's like, I feel sorry for everyone in here. But somehow, I do not feel sorry for myself at all.

And that's important, to take advantage of the situation you have and do that. And he's got a lot of good life stories and life lessons I've learned from him over the years. And I've said, if you don't feel sorry for them, then you shouldn't feel sorry for yourself-- or you don't feel sorry for yourself, you shouldn't feel sorry for them. You don't know why other people are here. But he's a fun guy, so it was actually a lot of fun to do that.

So we just talk about this right axis here, or this right side of the graph. I'm going to fill in the left axis. I'm switching topics here. I don't know if you want me to take all questions at the end or take them as we--

at the end.

At the end is fine, OK. So the other aspect we got into is waste to energy. So municipal solid waste rather than a type of biomass, so the rest of this stuff is going to be talking about landfill gas coming from this.

And there's a number of people that also study municipal solid-waste gasification as biomass. So there's some challenges and opportunities in that area, dealing with this rather than energy crops, which I may not highlight here.

So I'll put some statistics on this later, but landfills are basically large bioreactors that have a lot of methane and CO₂ coming off. So they're both greenhouse gases. Landfills are now starting to be required to recover this landfill gas, regardless of what they're using with it.

So a lot of times, they just burn it to make more CO₂, which is better than leaking out the methane. So this is becoming more prevalent. There's a lot of landfill law that I'm learning through this process, where they can try to circumvent the rules by opening new plots on the same older landfills.

So they have based off some established dates, which is how they based the law, rather than when the extensions are open. So there's a lot of interesting things here. I think there's a lot of room for waste energy on both routes of this, but we're focused on this one right now.

And here, this part becomes the same here. We're doing some gas production in fuel synthesis. I've been trying to do this primarily research on these two steps here, as well. And there's a number of people that are specifically looking at this route here, companies. Usually, they're large companies.

And I can unfortunately say there's been a lot of projects that have gone out that have been proposed and then not followed through on these. Some companies we follow and try to partner with it that are doing that are Solena Fuels, if you've seen that.

It's a British company, but they're trying to do the gasification of solid waste. And then, they've got some contracts with British Airways, Lufthansa-- and what's the Australian airline that are contracted?

Qantas?

Yep, that one. They had contracts with those. So everything that they're doing is they're trying to get their first production lineup in 2017 doing this route. They specialize in not just chemical gasification, but they're-- which one are they doing? They're doing plasma arc gasification.

So I've always heard-- I'm not an expert in that. That's challenging to make that economical, because it takes a lot of energy, but that's their thing. And then, Sierra Energy is a company out west that's also trying to do that. And they're doing oxy gasifiers. So they're removing the oxygen from air. And so there's some penalty in the process for that, and then using pure oxygen to gasify that. I think they also have a production facility plan for around 2017, where they're going this top route. But we're going to talk about this bottom route here now.

But there's some advantages, because there's some plastics you can mix in there. So that could help with the carbon to hydrogen ratio in using municipal solid waste, rather than the biomass. And you already have all the collection place and plan for everything to get it to one source. There is some advantage, and maybe that will come through.

So when we got involved with this, there were basically three options for landfills to deal with the landfill gas. So one is just environmental. So I'm going to include this later. And it's going to be a negative profit, right? If you build something just to combust it, it's going to be negative.

So we included that as a control case. So there's going to be some capital and some operation cost, but just the environmental mental benefits. So ideally, you would do something that would have an environmental benefit, but also making money.

So the one that's used most frequently is to burn it. And you heard that, and then heat steam to run everything, run electricity off that. That is good because you are able to get something out of it, but it's a challenge for two reasons whether people make money.

One being that the electric companies usually only pay about \$0.04 or \$0.05 to the landfill for the electricity. So that's about 1/3 or 1/2 maybe of what we pay for electricity. So they're usually-- because it's intermittent, so it's not necessarily good that way.

But then also, a lot of the companies that are trying to do this are based off of government funding for energy products. And the landfills we talk to say that those are slow in coming through, whether they're getting their bonuses for the environmental product. So any time you depend on the government to kick in for things, it's always problematic. You guys probably know that stuff better than I do, with your backgrounds.

And the other one-- this one's becoming more prominent lately, is a lot of garbage trucks are going to compressed natural gas, not necessarily liquid natural gas. So there's also have to consider how much energy it takes to compress this, to separate the carbon dioxide and compress this.

In any case, and we'll mention this. There's different contaminants in landfill gas that are in biomass, silicates. So this is something also I've learned a lot about talking with landfill people. Anything shiny that goes in your hair or on the cover of a magazine has silicates in it. And they form species that have a high enough pressure-- they can form gas-phase species, and they come out with the landfill gas.

So if you're running a turbine or something, silicates form in the blade. So even if they do the electricity, they have to replace the components quite frequently. So there's a lot of operation costs-- maintenance costs, I should say, that increase the operation cost of this.

So we did a simple math balance when we started this project. And we said an average landfill can produce about 7,000 gallons a day of diesel. And they would have a nice closed business loop system if they were use that diesel to power their diesel trucks.

I should mention the cost of trucks that run off these are very expensive, too. So there is some advantage for using the curve and the infrastructure if we can get renewable fuels from this route.

So I just mentioned a few times what landfill gas is, but we have a real table here from the EPA. So it's mainly carbon dioxide, methane. There's always air leaking in there, so you can see the oxygen and nitrogen are components. There's some hydrogen sulfide, and you see that one can vary quite a bit, based just like your variability in your biomass.

You have variability in what's in the landfill and what time of the year it is, and how hot it is, and all these things. It's usually saturated in water, and then there's another wide variety of different organics that can come out. So there is some challenge here with variability, as well.

And this is not the most fair comparison I have here at the beginning, because I think methane has a much lower lifetime in the environment than carbon dioxide. But in terms of just global warming potential, it's much stronger.

And currently, and this is, I think, from 2011-- I don't have the date on here-- this 17% of methane that leaks out of the environment is from landfills. So it's a pretty significant contribution to the environment, as well, on this topic.

One of our students calculated this, and I didn't believe this number the first time I did it. But you just take how much waste is in the US, and then how much landfill gas is generated from that. Six cubic feet per person of landfill gas is generated per day in the US. And I thought that was a shocking number. That seems like a lot.

So if you think of this in a personal level, it's quite big. I know that number's accurate, because I've seen that in several places, 250 million tons of trash. But that puts a real personal time frame on it when I think of six cubic feet of me contributing that per day.

And so you can see there's a calculator on EPA and some other websites, where you can figure out some of this information. But you can have a lot of opportunity to power homes. This is again, I think from 2011. But around [INAUDIBLE] houses per year, so a reasonable amount. A reasonable contribution to our energy. Maybe not the one solution, but a reasonable contribution.

And what we try to do in this is convert this as syngas. We have these reactions, these two primary reactions here. We have a little bit of steam to get our higher hydrogen to CO ratio. And then, we have a lot of-- oops, that's not the reactor. Let's hit the button one more time-- and we have a lot of carbon dioxide.

So we have a lot of steam. We had to add a lot of steam to get our hydrogen ratio to 3 to 1. We have a lot of carbon dioxide. This ends up being 1 to 1. So we balance those two reactions. There's a little bit of oxygen there, as well. We can get a reasonable hydrogen to CO ratio with only adding a little bit of steam to this process.

And so our goal is to first study this process here. So to get the right ratio to do liquid fuel synthesis, and see if this could compare with electrical generation. And so we made some catalysts based off of existing knowledge in the field of methane steam reforming.

So one of the component reactions that cerium, zirconium, and nickel magnesium is good. So we studied some aspects of this. We did several different formulations. In this case, this is how much hydrogen's coming off. So one of them was best. That's probably not much detail.

Here, we did a lot of characterization methods, which I took out, to figure out why that kind of material ended up being the most prominent of them. And this just shows we could get different species out if we alter the ratio.

So when we first tested this graph here-- we tested this catalyst here, we have probably the key component here is this hydrogen to CO ratio. We want this to be 2 to 1. So if we increase the oxygen a little bit, we can get the higher ratio. And we still have a high carbon dioxide conversion.

And if we increase the steam-- this is the steam content is now added. We're able to get the ratio we want there, 2 to 1. We still have a high CO₂ conversion. And if those last two lines that was added on there, we kept adding more steam. These numbers kept increasing.

And eventually, well, steam likes to react more than carbon dioxide. So if we put too much steam, we start having the carbon dioxide conversion. So in that case, we'd still have carbon dioxide coming out from the reactor, which we were trying not to do. So we had a number of situations there.

And this last column there is how much of the carbon ended up in coke. So solid carbon on the catalyst, we want that number to be small. So you can see there's some optimum ratio we got here. I guess this guy right here, we had 88% conversion of CO₂ and minimal coke formation.

So we used that catalyst. We wrote a paper on it, which is at the bottom here. And then, we had good fortune, I guess, on this. So there's a very interesting situation. I had two Master's students. So one was the first author on that paper back there, and he had business interests.

And then, another Master's student was a little bit older. He was a BS-MS student. He was a former bank worker, and he really liked all this crunching all the numbers of stuff. And I got an email one day about this Megawatt Challenge thing and I forwarded it to him. And I was like, come see me if you guys are interested. So they were in my office immediately.

So we decided we were going to submit something on this. And we were only experienced with this, so we asked Professor Babu Joseph, which was one of the collaborators, and his Ph.D. student, Ali Gardezi-- which I have a picture of him later-- if they wanted to be involved with this. They said, sure, let's give it a try.

So part of this thing was we had to form a company. We had to make a website. We didn't come up with-- the students really liked Trash2Cash, but that's taken for junk recycling and stuff. So we had to put the "-Energy" on the back so it was a new company. And then, we had to get a website for it.

And part of the things to be able to submit was we had to submit an IP. So we submitted the disclosure to USF that we wanted to use in this process. I'm new to patent things. They take a long time. This is still patent pending, even though it's four years later. So that's new to me.

And now here's the other part of this. A Professor John Wolan was also involved with this. He's passed away a couple years ago. But Ali was doing a Ph.D. With those two, and they had published a paper also at the same time.

So he's doing the second step, the Fischer-Tropsch synthesis. And they published this paper and another paper. And their patent has been accepted in the last six months. I think they submitted it in 2011, so about four years.

And these are all the carbon numbers. And they had a specific way where they design that coating up there to get the carbon cut around diesel fuel. so C-14, 16, 18 range there. Maybe not 18, but 17. And so they were able to make a new way to get this catalyst to maximize the production.

And so I jumped ahead of myself a minute. So we did this. We won \$10,000 to form the company and compete in the all-Florida competition. So maybe we were lucky, because this competition went regional after this to the Southeast.

In the year we went, last year, it was Florida only. So maybe we got lucky to win it with less competition. But maybe we'd still would have won. I don't know, probably been more challenging. So we ended up getting \$110,000 from this competition.

And we participated in two other things. And I got a headache dealing with this, because this money up here is to the company, and this money here's to USF for training students in entrepreneurship. But this is our goal.

So we have a couple of current students that are doing things related to the project, but they're training in entrepreneurship, as well. So it gets a little confusing. So here are the 10 companies. We ended up winning this competition, so it was actually very interesting.

So the students had to give the presentations. Devin was the Master's student I mentioned. He did everything on all the presentations. And then, one week before the competition, he started a job at BASF in Georgia. And he couldn't get off his first week of work to get that.

So we had to fly Tim in from California to give the talk, and people were very worried that we were flying somebody across the country to give the talk, that the Megawatt people had not met him. But then, they're like, oh, we like Tim just as much as we like Devin. And they ended up winning, so it actually ended up being very strong for us. But I think I like the competition, that the students have to get the talks. That's great.

And so we have to come up with all these things here. When I start getting into-- I didn't put all these terms in here. I don't honestly want to go through all these, but just to show that when I said the students are getting trained in entrepreneurship, the current ones, they're learning these competitive landscapes we have here.

We had some other terms I can't think of right now, but it seems like all these different trainings they go to, there's some different term. Something "business canvas," you guys know that one? I don't know any of that stuff. So they tell me they have to put what seems to me the same information, but it has to be in some different format for this thing.

So this is actually a useful one here, because it shows some of the companies that are doing landfill gas. And we're doing a lot of statistics here, like how many landfills-- well, I guess we knew how landfills are in Florida, but how many use this technology. And we know how many companies are going to L&G trucks in this process.

And we have what people are generally paying for electricity for this is low. We know how much these trucks cost now to retrofit diesel fuels with these L&Gs. So we have a good idea from this stuff, even though I'm making fun of the titles of them. We have a much better idea of all this competition.

So I come up with a business strategy here, starting in Florida. And 53 landfills here, 1,700 in the US. So what you said before is these are complicated flow processes. This is some of the students. This is particularly this student here. He likes to make things really complicated.

So he makes this gigantic thing and you can't read it. And I was like, can you make me a very simple thing that we can show in presentations? And I end up with this, which is still kind of complicated. So I wanted four boxes.

So we're doing some separation here. So this is we're trying to remove the hydrogen sulfide. And this is the first reactor that my group was working on. The second reactor, the Fischer-Tropsch one that Professor Joseph and Professor Wolen were working on. And we have to do some cut off the product. And we got into more depth through this.

So we'd advise the capstone-- that's like a senior design project in our department. They're supposed to come up with some novel process design. So usually, it's-- this case, he is the student that's doing all our entrepreneurship, so he found some teammates to work on this. And they did this study.

And they did a numerical thing, and they did a really nice job. And they compared to all these different technologies. So we do do some economics. I think engineers do economics and chemical engineers do economics in different ways than other people do economics. So do you guys know all the acronyms on here?

No, not everybody.

This is Discounted Cash Flow Rate of Return. So this is important. This is how much money you're going to make off a fraction. Net Present Worth-- Fixed Capital Investment is the one at the top. And

those are-- MM is a Million Dollars per Year. I get confused on that, because I use K and M, I think, in my own per, for 1,000 and million. But that's not.

So we are able to do this. Some of the assumptions are down here. We're going to diesel fuel. So the key part of this is we could make the most money, 25% down here, but we have the most unproven technology of all these.

But you have to do-- as these laws become more stringent, you have to do something. So you're going to lose money if you just flare it, which makes sense, because you're losing energy of the methane. But these other ones are about similar.

This one's probably the easiest. Professor Philippidis used the turnkey. These are becoming turnkey, so that's the challenge, that these are starting to be proven. People know they can make around 10% in income from this, whether they invest in their trucks. And this is going to shift this, even though it's the same value.

And then, we're higher, but we're not sure if we're high enough for people to make the capital investment or the technology investment, which I have shown here.

So here's my lab. This is where we do most of our more fundamental studies. So a standard cubic feet per minute there, so that's our volumetric flow rate. This is what the catalyst looks like when we're at these scales. I think that picture makes it look like fried chicken, but that's the color of the ceria zirconia. So these are small.

These are small particles. When you increase the scale of your reactor, you need to have larger particles, so you don't have pressure drop by having all the pores in there. So we need to make something like this.

That's what Ryan is a student I highlighted. We have another student with him. They're both getting entrepreneurship training on this, as well as doing some of the scaling-up. But we're trying to go for - this is like a large lab-scale reactor. See, that says factor of 50 there.

And then ideally, we would-- Professor Philippidis worked with Charlotte County. They've been saying that if we could make a pilot-scale truck on the back of a skid, they would send some landfill gas they have over there. We could test it, and that would be something that would be on the order of three standard cubic feet per minute.

It'll go from 0.1 to three. That's another factor of 30 we'd have to do, and then go up by a factor of 1,000 there at the end, if we wanted to go directly to full-scale. So we have some challenges in this. It's unproven for this process. We need to have some benefit there.

And we're doing some other research areas. I've had to do this. I have two Ph.D. students there at the top and undergrad students who are trying to do process intensification, which is basically trying

to take these two processes and instead of having to build all the infrastructure for two reactors, to do it in one reactor with some special catalyst.

So there'd be some advantages there-- if we could do this-- to reduce the capital cost, because we have better integration of the waste heat between the high-end exothermic and endothermic processes. And I've probably talked for-- probably used all my time now, so maybe I'll stop here if you guys have any questions.

Do you think that you will do the scale-up in Charlotte County? Is that something you think will happen?

Well, they have been very nice to work with, on giving us information and things. So if we're able to do the scale-up, we'd like to do it there. It's not too far away. Whether we do that is going to depend on whether--

money--

money, yes. So I think we can build that facility, which we could build something along these lines for that scale on the back of a truck. We could build that for \$500 to 2/3 of a million. so right now, our route has been trying to go for SBIR. The phase two happens to be around that amount, so it'd be something we could do.

I think they want us to partner with people or have investors. They want more buy-in before we go there, so we're learning a lot of those things.

Will whatever you produce just go back to Charlotte County, and they would use it for electrics?

That's a whole another thing, whether we own the plant and operate it, or we hire. So that's another-- we have a threefold business plan, depending on who we talk to. So the advice we got was to deal with public entities and not companies at the beginning, because you can have a little bit more flexibility with them.

But we also had talked to some-- like Waste Management would be-- they're big enough to buy what they want, I guess, right?

Also, John, at that specific landfill, there is a company that is producing power?

Yes, yes. So we're not necessarily talking about setting up a facility, but testing the pilot-scale facility. So they preliminarily said it would be OK to do that. But we're talking about small amount-- small times, gas. A small amount of time for a month or so just to test at one time.

Yeah. They wouldn't use all of it, though. Maybe they use part of it.

Yes. But for that, we need to target companies that are just flaring or investing the first time, right? If they're already doing electricity, than our numbers for economic comparison are no longer valid, because they already invested the money, right?

Can you give us an idea of how expensive catalysts are, so that--

so that's a great question, because a lot of research is trying to replace precious metal catalysts with non-precious metal catalysts. And it ends up being a small amount, if you're talking about overall process.

So first, oil companies are the best people at recovering platinum. They use a lot of platinum in processes. They're really good about reusing all of those species. In terms of a number, usually-- so if you think about a process like this, there's two reactors in there. The fixed capital investment for the catalyst is probably 1% or 2% of that operation.

So like this, 2% of the cost of that is the catalyst in there. So it ends up being not a substantial amount in the overall process, once you have separations and everything.

The thing where it comes in probably more is depending on how often you replace it. Ideally, they only replace it once or twice a year. So sometimes they last longer. Sometimes, they last less.

In the context of sustainability, we spoke about whether you can regenerate the catalyst. can you maybe elaborate on that?

So the more expensive the catalyst, the more likely you are to be able to reuse it. So in terms of anything-- in this case, our catalyst is unfortunate. We use a ceria, which the US does not have a lot. So it's something that people are investing in. That's called a rare earth element.

A lot of the rare earth elements end up being in China, so they have a lot of control over those things. So there's some amount to be able to reuse those sparingly. So those type of things are good to reuse.

If you look at-- in your slide, you had some things related to olivine, and particularly dolomite. Those are just use and throw away, they're so cheap. So you don't even want to bother. And that's why they end up putting them in the gasifier, even though they know they're going to fall apart. They're cheap. We have a lot of minerals. We can just put them in there and not worry about them.

Europe's ahead of us in this. So when we talk about replacing metals and using less platinum, using less of these precious metals, they're ahead of us. And they count things like cobalt, which we count as base metals. And they call those metals they shouldn't use. And nickel.

So nickel. So in gasifiers, they're not supposed to use nickel and cobalt in there. Those are common go-to catalysts in these, which we consider those as good catalysts to use. And they're talking about only using iron and silicon and things like that.

So to answer your question specifically, I think any catalyst that's not falling apart physically in a gasifier, if it's just poisoning, can be regenerated and reused several times for a few years at least, but it depends on just how much it costs.

In petroleum processing, sometimes catalysts poison very fast, in five seconds. And then, they have to build reactors a different way, where you have a reactor to regenerate, and a reactor to use it. And they cycle back and forth.

So if you guys ever heard of Fluidized Catalytic Cracking, FCC catalysts, those get coked up in five seconds. So they have a very elaborate process to cycle them back through. So there's other ways to do that, as well.