Evaluating Changing Paradigms Across the Nuclear Industry
Dr. Jessica Lovering, Carnegie Mellon University, USA and Winner of the ANS 2020 Pitch Your PhD Competition

Berta Oates
Welcome everyone to the Next Gen IV International Forum webinar presentation. Today's presentation on 'Evaluating Changing Paradigms Across the Nuclear Industry,' by Dr. Jessica Lovering will be presented.

Before we get started, there is some housekeeping information that we'd like to go through.

Doing today's introduction is Dr. Patricia Paviet. Dr. Paviet is the Group Leader of the Radiological Materials Group at Pacific Northwest National Laboratory. She is also the Chair of the Gen IV International Forum Education and Training Working Group.

Patricia?

Patricia Paviet
Thank you so much, Berta.

Good morning or good evening, everyone. It's a real pleasure to have Dr. Jessica Lovering with us today. She is the American Nuclear Society winner of the November 2020, 'Pitch your Ph.D. Research'. I am very happy that she is with us, contributing to this webinar. It's important to have the younger generation presenting as well as the other more senior scientists.

She is the co-founder of the Good Energy Collective, a new organization working on progressive nuclear policy. She recently completed her Ph.D. in Engineering and Public Policy at Carnegie Mellon University. Her dissertation focused on how commercial nuclear trade affects international security standards and how very small nuclear reactors could be deployed at the community level. She is a Fellow with the Energy for Growth Hub, looking at how advanced nuclear can be deployed in sub-Saharan Africa. She was formerly the Director of the Energy Program at the Breakthrough Institute, a pioneering research institute changing how people think about energy and the environment.

Thank you so much, Jessica again for volunteering to give this webinar and I am giving you the floor. Thank you.

Jessica Lovering

Thank you, Patricia for that introduction and thank you to the Generation IV International Forum for having me.

Let's see if I have control. There we go.

The talk I'm going to give today is a little bit of a condensed version of my dissertation. I've tried to keep just the most interesting parts but I'm looking forward to plenty of time for questions at the end.

To get started, this maybe obvious to people but I think it's important to say again that the world needs a lot more low-carbon energy. The Intergovernmental Panel on Climate Change argues that the global energy system needs to reach net-zero emissions by 2050 to avoid the worst impacts of climate change. For that reason, the International Energy Agency has concluded that global nuclear capacity would need to double by 2050 to keep the world under 2 degrees of warming.

The power sector should be the lowest hanging fruit for complete decarburization due to the diversity of low-carbon options that we have. But even here, the world is not on track, and that's what I'm showing in this graph on the right. This is showing the global share of electricity coming from low-carbon sources and you can see that it's been kind of flat, around 36% since the 1980s. There's been a lot of stagnation and even decline of nuclear generation in the West, and that's part of what's led to this stagnation in low-carbon energy globally but there is a very large potential for growth in emerging economies, and that's what I am gonna focus on for a lot of this presentation.

Okay. This potential for new nuclear in emerging economies is really highlighted by this map which is from a study that was done by the think tank, Third Way and Energy for Growth Hub. What they did is, they projected that global electricity demand would double by 2050 with over 90% of that growth coming from outside current high-income countries. What's interesting is actually most of that growth is in countries that are interested in nuclear and will likely be ready to host their first nuclear power plant by 2030.

So, on this map – and this is an interactive. You can find it on the Third Wave website if you want to play around with it. The size of each circle represents the magnitude of the projected increase in energy demand for each country and the colors, the readiness for nuclear, and so you can see how those two projections overlap. What's important here is that almost every country that starts a commercial nuclear power program, first imports the technology from one of the big vendor countries. And this will likely be the case for most of these newcomers as well.

What's interesting for our work is that most of these countries that are pursuing commercial nuclear power already have agreements in place with Russia and China, so-called nuclear cooperation agreements or memorandums of understanding. They vary on how concrete they are, how much they are about safety and security or whether they are about actual trade in commercial nuclear reactors, but not a lot of these countries have agreements with the US.

I know we've got an international crowd today but I am going to be a little bit focused in this first part on the US's role in the global nuclear market and what that looks like going forward. This map is from a great report from the Global Nexus Initiative that I encourage you to check out if you haven't seen it already.

This trend of the US being somewhat 'absent' from the global nuclear market has been going on for a long time. This chart that I am showing is the total amount of nuclear exports by decade and by country. This is commercial nuclear reactors by gigawatt.

And you can see, this light blue color is US exports and the US was the dominant exporter for the '60s and '70s but then it's declined to very little. Whereas Russia – it was the Soviet Union here, but Russia now has sort of maintained a good share. We're just starting to see South Korea. France has sort of maintained their share, and China's actually on here with their one project in Pakistan but it's too small to show up but they have big ambitions. So, China and South Korea have big ambitions for exports going forward.

You can see a similar trend in all sorts of data – nuclear R&D by country, nuclear patenting, fuel exports, research reactors. And why this is this is interesting to us is that it has a lot of implications about this geographic shift in power, and what that means for international security/safety/nonproliferation regimes. And so for the first chapter of my dissertation, this is what I looked as the implication of this trend and what sorts of policies could be implemented to strengthen US influence going forward.

This work has been published. It was published last year in the journal on Energy Policy. So if you are interested in this side, I encourage you to read that paper. But the main question that I was asking in this research was, what was the role of commercial nuclear exports in setting international safety, security, and nonproliferation standards, historically? What strategies might strengthen US influence in global nuclear security regimes, and how effective and feasible are these strategies?

I am going to go through this work pretty quick because I think you'll probably be more interested in the micro reactor stuff, and this work has already been published. So just big picture. We developed a series of strategies. You can think about these as a sort of policy packages for strengthening US influence in international regimes. And to evaluate them, we brought together this participatory workshop of experts in September 2018.

It was at 2-day workshop with experts from a mix of nuclear energy and security fields. We also pulled them from think tanks, academia, government. There were pre-readings and introductory presentations to frame the conversation, and then our experts evaluated our foundational premises – kind of our assumptions – around these historical trends, and then the six proposed strategies that we put forward. They also brainstormed four additional strategies that were evaluated along the same format.

I am just going to jump to the big results from the workshops. Going into this workshop, a lot of the literature on, especially coming out of US security space and US nuclear energy thought leadership was really focused on export control as the big obstacle for the US. We could be more engaged, we could be doing more commercial exports, but our export control is just too constraining.

From our group of experts, export control was really not seen as the main obstacle. They thought we just didn't really have a product worthy of export or that we couldn't do big nuclear export projects, so the focus was really on how do we sort of reinvigorate and strengthen the commercial nuclear sector so that it's competitive with the other big vendors globally? Unfortunately, expensive, and radical policy programs to commercialize new reactors were not really seen as feasible – maybe that sounds surprising.

We did put forward a few diplomatically focused strategies and these were viewed as much more effective at strengthening US influence but especially difficult at the time – this was during the Trump administration, so not very feasible to implement, although they did think they could be implemented with a different administration.

But the big takeaway overall was that the experts just didn't think the US could compete with large light-water reactors.

That last phrasing is key because there are a lot of non-light water reactors under development in the US and they agreed that advanced nuclear technologies could be cheaper/faster/safer, the US could have an advantage if they could get them commercialized. This map is from a report from the think tank, Third Wave. It maps out advanced nuclear projects under developments. It's now worldwide if you want to look at it.

But the US has over 60 advanced nuclear companies working on commercializing new technologies, and so the question that we discussed with the experts is, are any of these going to ready fast enough, in time to be competitive on the global market? The experts were a little skeptical on that front for those that were familiar with what was going on with commercial nuclear.

There was a lot of skepticism about how fast these technologies could be commercialized. And the two concerns were really founded in existing literature and evidence. The first is from the Secretary of Energy Advisory Board from 2016. They found that commercializing a single advanced reactor design in the US could take decades, and cost about $25 billion. So, they didn't see that the US would be willing to commit that type of money to commercialize a single reactor design.

Then there's a complimentary paper from Abdulla et al. 2017 that found that the US government has not been investing nearly enough to commercialize advanced reactor technologies. So at the time I wanted to look into a little bit more at how fast new nuclear technologies could come to market. If that's changing? There were really two big trends that stuck out that our experts really didn't know about; they didn't know the status of what's going on with advanced nuclear in US, which is moving very fast.

Two things that we kind of highlighted after the meeting is there were several advanced reactor vendors moving towards licensing in the US and Canada, especially small and very small modular reactors. Since this workshop, there's already been some licenses submitted and there's a big move towards private funding and financing, and seeking niche markets to build a commercial demonstration, without government involvement, and on much shorter timescales. So, I wanted to explore how this might change the export market and the US's chances of being competitive. And in particular, I am going to focus on very small modular reactors because they seem to be able to maybe move a lot faster than even SMRs.

For the rest of the presentation I'm going to be referring to these as microreactors. I know in Canada and other places they call them vSMRs but what we're talking about is anything smaller than 10 megawatts electric. There's a lot of other properties that go in there. But what we found is that microreactors could be a marketable export product, and they might also come with some security and nonproliferation benefits, so it's worth exploring.

Most of the main nuclear vendors – the big countries are focused on large light-water reactors, although of course there are some great SMR programs around the world. In the US we do have several companies – it's growing up to maybe more than dozen now – private US companies working on microreactors, and they are aiming to commercialize and demonstrate even faster and earlier than SMRs, and definitely before large, advanced nuclear technologies. And they could have some international security benefits.

A big one that I would like to focus on is lifetime cores. This means that there's no on-site refueling, and this could help facilitate a Build-Own-Operate-Remove export model, which could be very attractive for certain countries, it could get commercial nuclear into countries much sooner than large light-water reactors. And importantly, this BOOR model avoids many of the security challenges in nuclear newcomer countries. You don't need to develop domestic fuel handling and waste storage facilities, so that could be very beneficial.

I said that microreactor developers were targeting niche market, so they are looking for places that pay a lot for energy already, and so even the first-of-a-kind cost of a demonstration might be cost-competitive, with existing energy prices. There's only a few places where this might work but one of them is in diesel-dependent off-grid communities, so islands. But also, certain countries like Canada have a large number of off-grid communities that are dependent on diesel.

This is a map of them. The blue lines here are the existing power grid and the circles are all the off-grid communities. And the population actually adds up to quite a bit but their individual electricity demand in these communities is quite small, it's even too small for an SMR in most cases.

So, what I wanted to look at with the second chapter in my dissertation is, could microreactors actually make sense for such communities?

And so the questions that I was looking to answer with this work were, under what conditions would a small nuclear reactor be the optimal choice for a microgrid installation, specifically an off-grid application? What would the microreactor need to cost to be cost-competitive with alternatives for microgrids, that's mainly diesel but also renewables and batteries? How important is load-following for microreactors? Because again, they might be operating alone on a microgrid or with renewables. And how sensitive is this optimal choice to diesel fuel prices, and then parameters of the micro reactor?

Just at first glance, very simple estimates. It looks like microreactors could be cost-competitive with diesel and that's why these companies are looking at diesel-dependent communities. This bar chart here is just showing a really rough estimate of levelized cost of electricity for a microreactor and for the range of diesel generation globally. You can see that for diesel, almost all the cost is in the fuel, and this bar here represents the range of diesel prices globally, so it's a very big range.

For the microreactor, for his chart, I just essentially doubled all the costs of a light-water reactor and that's based on public numbers that I've seen, just rough estimates, to give us a first order approximation. It looks like it could be competitive but we really want to know what capital cost, what load factor, what diesel price is this true at the local level? That's rendered a much more detailed study for this research.

What I wanted to do was actually model some real communities that might use microreactors, and to do that I used this software called 'HOMER' that's developed by the National Renewable Energy Laboratory here in the US. What HOMER does is it finds least-cost grid mix to meet a specified electrical and thermal load, if you have it, based on the generation options included. It does hourly load, so you have to have a year's worth of hourly load for the community you are looking at, and then it makes sure that your mix of technologies can meet that load, and then it optimizes over cost.

What's nice about HOMER is it includes a very big catalog of generic technologies, renewables, fossil, battery with cost and performance, as well as links to weather data, and renewable resource data by locations. So you can get very granular data for this community and you need that weather data for things like battery and thermal performance for your generators.

I was able to get real data for a set of case studies. I had two communities in far Northern Canada that are currently off-grid, diesel-dependent communities. I am calling them 'Community A' and 'Community B' but they are in Northern Quebec, and their loads are just a few megawatts on average. I also did a large hospital complex in Fairbanks, Alaska, and then I had the University of Wisconsin, Madison Campus – I wanted to do a college campus just to see what it looks like.

These latter two cases are grid-connected, so it's harder to make the case for a microreactor. But I just wanted to see how the performance looked for microreactor. For the rest of the presentation I am going to focus just on 'Community A' to show you what the results look like, and you can see the other results in the paper that's coming out soon.

For each of these case studies what I did is I modeled for microgrid systems, constraining the deployable technological mix in each to compare their cost and performance. What HOMER does is it optimizes with whatever technologies you allow it to have in each case.

The first mix was the business-as-usual. It was 100% diesel. I did over a range of fuel costs to test the sensitivity. The first mix, Mix 1 was 100% micronuclear. HOMER actually doesn't include nuclear. This maybe not surprising, it is a renewables-focused microgrid program and most people don't think about nuclear when they think about microgrids but it does allow for you to make your own generator. So I developed a generic 1 megawatt microreactor component with nuclear-specific parameters – heat rate, fuel density, fuel cost things like that – taken from some NEI reports and IEA reports.

After the 100% micronuclear case, I looked at nuclear with diesel, so allowing HOMER to optimize over microreactors and diesel generation. And the last mix was nuclear and batteries because there are some people arguing that batteries could be a good complement to nuclear for load-following.

All four of these cases, I first did without and then with renewables included. It's just easier to do the optimization separately to see what changes and I will show them those results. I will point out that this community is very far north and it's very cold in the winter. So renewables didn't make a lot of sense but that's not going to be true everywhere of course, so just that with that caveat.

The big results here were that the optimal system really depends on your constraints but nuclear with batteries was the cheapest option and the cheapest low-carbon system. So depending on what you care about – if you just care about lowest cost or if you care about low emissions, and whether or not you want to include nuclear or exclude nuclear from the system, it changes what your optimal system is. But you can see here that because the micronuclear was cheaper, specifically cheaper than diesel, it's both the lowest cost and the lowest emission system.

The optimal system here was actually 3 megawatts nuclear, so three microreactors, and then a very large battery within, it gives an LCOE of $0.16 per kilowatt hour. Now if you exclude nuclear, the cheapest option is going to be diesel with a good amount of wind but of course that wind comes and goes, so that's why you still need that 4.1 megawatts of diesel.

Now, if you really want to exclude nuclear and have a low-emission system, that really gets really chickpea [ph] in a community like this. You have to very much overbuild the renewable system. So the optimal system for 100% renewables includes 54 megawatts of PV, 21 megawatts of wind, and a 325 megawatt-hour battery, which is huge, that's larger than the largest battery installation currently operating, although that might be eclipsed soon. And the levelized cost, as you can see, was over four times greater. So for communities such as this, which is very far north in a very cool place, nuclear and batteries makes lot of sense for them, and it's definitely cost-competitive with diesel.

Of course, we don't really know how much a microreactor is going to cost. So I did a very large range of potential costs that I justified based on a lot of literature and projections, but it's really going to depend on what these costs end up being. I did a sensitivity analysis on all the parameters related to the microreactor and the diesel generation, and this chart is trying to summarize a lot of them at once, so bear with me.

This chart is showing the levelized cost of electricity from the microreactor as a function of the operating reactor lifetime, so how long that core lasts before you need to replace it. And the capital cost of the microreactor, ranging from $5000 per kilowatt to $25,000 per kilowatt. This grey bar is the range of diesel LCOE. If your fuel goes from $1-$2 per liter, that's kind of a rough range that we see in this region.

Some of these communities are even above $2 a liter, some communities that are closer to the grid or closer to the road network are maybe a little lower than $1. But this is kind of the range where you need to be for the micronuclear to be competitive. You can see that the microreactor is cheaper than diesel for operating lifetime sort of above 10 years to 15 years and for capital cost sort of below 15,000, below 20,000. So that's sort of roughly the parameters that need to be met.

The big takeaway is that microreactors can be cost-competitive with diesel if – that's a big 'if' – capital costs are moderate and diesel prices are high. So microreactors are currently not competitive with grid electricity. That comes from those other two case studies I did. They need a carbon price of about $60-$120 per ton. And largest uncertainty really comes from capital cost and also the lifetime refueling model, so what the business plan is for the core lifetime.

This is a sensitivity chart showing how much the LCOE changes when you change each of these factors by 50% – so the capital cost, the lifetime. Operations and maintenance has an effect, but it's smaller, and then fuel, which has a very small effect on the LCOE. Okay, so how much are these things going to cost is the big question.

There is a lot of concern in the literature of microreactors which there's only very small literature on microreactors, I will caveat. But there's a feeling that they have to be very expensive because they are so small. This assumption really comes from assumptions about economies of scale. But proponents argue that factory fabrication in economies of volume – so, for the last chapter of my dissertation what I wanted to look at is tradeoffs between economies of scale and economies of volume for very small modular reactors.

So the big questions that I am answering in this chunk of research are, 'do nuclear reactors experience economies of scale, and how large is this effect?' 'What learning rates are expected for factory fabricated SMRs?' 'Can economies of volume from factory fabrication offset potential diseconomies of scale?' 'And where is the breakeven point where it makes more sense to do factory fabrication and where do they break-even on costs?' And then sort of the big question from the previous work is, 'what is the potential range of capital cost for Nth-of-a-kind microreactors?'

And parts of this work have been published in 'The Bridge' a National Academy of Engineering journal, if you want to go into a little more depth on that.

They said there's really no consensus on cost of future SMRs from experts. This chart is from an expert elicitation of Nth-of-a-kind nuclear cost from Abdulla, 2013. What they did is that they asked experts how much different sized reactors will cost Nth-of-a-kind? They are kind of all over the place. This is a large 1-gigawatt light-water reactor but they also looked at a smaller 45-megawatt SMR. You can see it, it's all over the place. But that is still much larger than a 1-megawatt microreactor.

So some of the costs that we've seen recently – yeah, there's NuScale, there's a lot of different estimates for NuScale that have come out as they changed their reactor size and they changed their projections. But at the time this was published, I was seeing 4400 per kilowatt. And Oklo, which is a 1.5 megawatt microreactor, in their license application they give an estimate of 6700 per kilowatt, so that's pretty cheap for a microreactor. But you also see in some of these studies that are microreactor-specific, much higher costs.

This paper, Moore, 2016, which looks at microreactors in Canada, uses US $35,000 per kilowatt. And Froese et al. uses $130,000 per kilowatt. Now this is very high and where they get those numbers is by using scaling relations.

We are going to explore a little bit more about these scaling relations. And just to warn you, this is going to be my only big slide full of math, so bear with me. There are two main equations that govern the economics of nuclear costs in theory, and those are scaling relations and learning curves.

This equation on the left is a very standard scaling relation. This is used in all kinds of engineering, all different types of technologies. And what it says is the cost of the smaller unit can be scaled based on the cost of the larger unit – based on the size difference and then to the power of the scaling factor. So obviously, everything comes down to what the scaling factor is for a given technology.

This equation on the right is maybe more familiar to a lot of you. That's a traditional learning curve equation. And again, we see this learning curve applied in all sorts of technologies. It was originally developed for airplane manufacturing but we see it for solar panels, and wind turbines, and jet engines and all sorts of things.

What this says is as you build more units of a technology, the cost comes down. The more intuitive way to think about it is the learning rate. And what the learning rate is, is when you double production of a technology, how much does the cost decline, by what percent?

There are estimates for both the scaling factor and the learning rate for nuclear. In the literature there's dozens, if not hundreds of studies on each of these. But from the literature, on nuclear, we see a scaling rate of about 0.25-1.0. 1.0 means there's no scaling effects.

From the literature on learning curves, we see learning rates ranging from negative. Meaning, technology gets more expensive the more you build, to positive 6%. So that's a big difference and it really changes how we think about factor fabrication of nuclear.

Now, the big, big problem with this literature is that it's almost entirely based on the US cost history from the 1970s. Even though there's at least 30 studies that look at scaling relations, they are just different kind of formulations or estimates of the US cost experience. So it's a very narrow range of technologies of history that we have evidence from. We don't have a lot to work with here in terms of what we might project for future technologies. But I just want to look at this assuming these are true.

To start, let's assume that scaling relations apply. If we do that, microreactors are going to be too expensive if these traditional scaling relations holds. So what I am showing here is and the first-of-a-kind cost for any microreactor, based on the capacity, the size of the unit, and then using the scaling relation with different scaling factors from the range that's in the literature.

This is based on the large light-water reactor that I am using in the scaling relation is kind of rough approximation of an AP1000, so 1100 megawatts. And you can see that down here for microreactors, the first-of-a-kind cost gets really high, up towards over $100,000 per kilowatt. That's where those numbers came from in those studies I cited earlier. And even for a traditionally-sized SMR of 300 megawatts, still double the cost of a large light-water reactor and also still too expensive to be competitive with grid electricity of course.

But there's an interesting phenomenon that maybe makes intuitive sense but we are starting to see it reference more in the technological literature. There's this idea that learning rate may also be dependent on size, more so than intrinsic to a technology. I think this makes sense – you are building smaller things on a factory setting, you learn faster, the smaller they are.

These are two recent studies. This one is Sweerts, 2020 and Wilson, 2020. What they did is they collected learning rates from a bunch of different energy technologies across the whole energy sector: demand storage, supply. And they compared the learning rate verses unit size. What they found is that learning rate goes up the smaller the capacity of the technology. Both studies find these different technologies, different studies, but they find the same relationship.

What I looked at is how this might apply to nuclear, specifically SMRs. So how might a learning rate that's based on size change how we think about these breakeven costs.

Also, unit size, so how big the reactor is can make a difference in cost to clients because you can just build more units for similar investment. What this chart is showing is how many units of an SMR you need to build to reach cost-parity with an AP1000 reactor? So not really any learning, very small learning for the AP 1000 but the same learning for the different sized reactors. And you can see that this is how many megawatts you need to build.

So obviously, if you are going to build 100 megawatts of a 1.5 megawatt microreactor, it's a lot more units of the technology. But that means the cost to client is much faster. So the smaller your reactor, the fewer megawatts you need to build to reach cost-parity with your large reactor. Again, this is assuming economies of scale applies.

But looking at different cost trajectories and different factors that influence them, cost trajectory really depends a lot more on learning rate than first-of-a-kind costs. This chart on the left is showing kind of a generic SMR with learning curves based on different learning rates from 1% to 25%, sort of the range we see in the literature.

And you can see that as you build more units, the cost comes down much faster. For higher learning rates that's obvious. But it's a much more noticeable change than if you changed the first-of-a-kind cost for the microreactor, for the SMR.

What we found overall is that learning rate is much more important than first-of-a-kind cost because a lot of the focus in sort of the cost estimates for microreactors for SMRs is really on that first-of-a-kind cost. And people think, 'Oh, that first-of-a-kind cost is too high, they won't be competitive,' but there's a lot more that goes into that.

Putting this all together, a kind of the $1 million question for microreactors is, how many units you need to build to be cost-competitive? Really to be cost competitive with grid electricity, I kind of chose this arbitrary target of $2000 per kilowatt. That's a good cost target for new nuclear. What I calculated here was, how many units you need to build to reach that target depending on the learning rate, and the first-of-a-kind cost.

You can see that if you start pretty moderate at $5000 per kilowatt and you have a high learning rate, you need to build 10-100 units before you get down to $2000 per kilowatt. But if you start high and have a low learning rate, you need to build tens of thousands of units to reach that $2000 per kilowatt cost target, and that could be much more difficult.

But this is sort of a big caveat here – the point I want to highlight is that this is units, not megawatts. So if you are building a 1-megawatt reactor, that's a lot less investment, a lot less cost to bring the cost down the learning curve. Whereas, if you are building a very large reactor, even an SMR, it can cost a lot more money to drive down this learning curve because it's really dependent on learning rate, which is just units built. That's sort of the big takeaway is that the smaller you build, the faster you can come down the learning curve.

To synthesize all this work and bring you back to where we started in the beginning, the experts who participated in our workshop agreed that US commercial nuclear exports helped strengthen international nuclear security regimes historically. But they didn't see the US being competitive with Russia and China going forward, particularly because of our lack of a vibrant export market of technology commercialization.

Microreactors could offer security benefits and an attractive export product compatible with a BOOR model for nuclear newcomer countries if they can be made cost-competitive. It looks like microreactors could be cost-competitive with diesel for off-grid applications. But to scale up and be cost-competitive with grid electricity, costs will need to decline significantly. It like such cost declines are possible, if economies of scale don't apply to novel designs, and if learning rates are above around 20%.

My Ph.D. was partially in public policy. So I did want to end – this is my last slide – on some of the policy implications or recommendations to facilitate this.

There's this good paper by Breetz in 2018 and that argues that both components of experience curve, so the cost and the deployed capacity, are affected by policy and politics. They are not just something that's intrinsic to the technology. Therefore, if we want to bring down the cost of nuclear, we need policies that facilitate deployment across the commercialization timeline.

We need demand-side policies that foster these first few dozen builds and have that concrete order book in place. We need modernization of licensing that is appropriate for mass produced reactors. And we'll need new export regimes for Build-Own-Operate-Remove models with SMRs and microreactors. Of course, the levelized cost is also really dependent on the cost of capital. Another thing that's important is support for financing to bring down the cost of capital to reduce the discount rate in that LCOE calculation. There's lots of other things and we can talk about them and in the Q&A but that's my last slide.

I am going to kick it back to Berta.

Berta Oates
Thank you, Jessica.

If you have questions, and I know there are several in the Q&A pane already, type those in now. And while those are coming in, we'll just take a quick look at the upcoming webinar presentations.

In August, a presentation on 'Graded Approach: Not just Why and When, but How.' In September, 'Experimental R&D in Russia to justify Sodium Fast Reactors.' In October, 'Metal Fuel for Prototype Generation-IV SFR: Design, Fabrication and Qualification.'

Give me just one second, Jess, I'm going to get you.

Okay so in the questions pane you now have access and should be able to see those come in. The first question, 'Does Russia policy of leasing or taking back their spent nuclear fuel play a role?'

Jessica Lovering
Yes there's a lot of extra services that Russia offers that make exports from them very attractive and cooperation agreements with them very attractive. China has been looking at doing something similar, and so has South Korea in terms of helping with financing, helping with supply chain. Fuel takeback is a big component, and that's something where we see the US is really at a disadvantage because not only do we not do fuel takeback but we also don't have a very small domestic fuel supply and no domestic policy on nuclear waste.

So that is one area where different models of SMRs and microreactors going forward from the US could make them more attractive export products if you can do this Build-Own-Operate-Remove model where you take the microreactor back – the whole thing back. Countries really like that idea, especially much smaller countries that don't want to develop their own fuel-handling and fuel-processing facilities.

Berta Oates

All right, thank you. The next question deals with private-level funding. They have the confidence in the private sector but not in the government laboratories.

Jessica Lovering
No. I think there's wonderful capacity in the national laboratories. They are not as set up to do commercialization, and that makes sense. They are doing early-stage research and they are helping remove the risks of a lot of these technologies – the development risk and financial risk of a lot of these technologies and figuring whether they need to be commercialized.

But in terms of turning a technology into a commercial product, that's something that private financing and private investors are better at seeing and understanding the market needs, developing business models that meet those market needs, understanding what utilities want, what customers want from nuclear technologies makes more sense in the private sector.

In the US of course it's different than most other countries. We have a very robust startup ecosystem, with a lot of venture capital and private financing. There's also just a lot of excitement around climate tech and clean energy. And so there's a lot of money that's going into all sorts of solutions on the clean energy side, and so there is a growing set of investors that are very interested in nuclear technologies. And you see this at kind of every level – traditional venture capital but also angel investors and kind of newcomers to the climate tech space.

So it's not in place of government investment, it's just different parts of the commercialization timeline.

Berta Oates
Great answer, thank you. How is the capital cost of microreactors calculated to compare with the diesel generators?

Jessica Lovering
For the modeling that I did with the microgrid systems, I used a big range of estimates for nuclear fuel costs, nuclear O&M costs taken from existing industry. But I made it much larger because we don't quite know. And then I used a big range of capital costs for the microreactors in those. So I did just a lot of sensitivity analysis but the kind of baseline costs that are used for a lot of those like the middle of the road, for those case studies it was $10,000 per kilowatt for the microreactors.

I think that's what the question is asking. And then, I did the same for diesel. I used a big range but I also for the baseline I used the cost of diesel in those communities, so the real cost of diesel.

Berta Oates
Great, thanks. I don't know but I hope we can go back to Slide 18 – this question actually references Slide 18 what nuclear modeled…

Jessica Lovering
I don't know what's happening.

Berta Oates
Yes I was struggling with trying to figure out if there was a typo in that word or that’s a word I'm unfamiliar with.

Jessica Lovering
I don't know. I developed this generic 1-megawatt microreactor. And what HOMER does is it picks the optimal number of those microreactors to build in the system, to make the lowest cost grid that meets the hourly load over the whole year.

Okay, maybe they can ask again.

Berta Oates
Yes. We have some clarification there. The reactor factor to be built, do we need DOD to order 1500 reactors to justify building the reactor factory?

Jessica Lovering
No, not necessarily. For any of these, the first few are going to be bespoke. They are going to be custom-built or hand-built. You probably only need maybe more than 10. For some of these companies, especially the smaller side, that's really their focus right now is building out their order book. So Oklo, the 1.5 megawatt reactor plant is looking at customers beyond their first few demonstrations. You do need an order book of some length to justify those investments in the full factory. But part of that early learning curve is your first few – maybe your first several are going to be more custom-built. And that does allow you to do a lot more learning in the early stage, before you commit to a factory and a really standardized design.

It's probably not going to be DOD also because it looks like we are going to keep the defense and civilian microreactors separate for the most part. There might be some companies that do both. But yeah, you definitely do need an order book and we know this from looking at learning curves for a large commercial aircraft. But how long that needs to be? It can be just a dozen or so units.

Berta Oates
Great, thanks. John Kelly has a question, 'Is there a theory on the economy of mass production that is different than the economy of scale?'

Jessica Lovering

Yes. It's called, 'Economies if volume,' and that is the learning curve. That is when you build something in a factory, the costs come down with more you build. We see learning curves for all sorts of different energy technologies. We don't really see them for large nuclear but that makes sense because we haven't actually built nuclear in a factory setting, so why would we see learning curves?

With regards to the scaling relations, the scaling factors that were calculated were over very narrow range of sizes, so sort of above 500 megawatts. It's really unclear if that same scaling relation applies when you get to very radically different designs like a microreactor. The scaling relations are really meant to apply to the same technology. This is just a different size. So you take an AP1000 and you scale it down to 1-megawatt. That's obviously not what's being done with microreactors but that's what's baked into those scaling relation assumptions.

So, I personally don't think that scaling relations apply over the full range of sizes for nuclear reactors from 1 megawatt to 1.6 gigawatts. But you definitely could see some diseconomies of scale with SMRs. But how big of an effect that will be is up for debate, especially if the engineering is much simpler.

Berta Oates
Great, thanks. There's a question, I'm going to reword it just a little bit – my apologies to the person who asked it. Are you optimistic about the investment, given a 6% learning rate?

Jessica Lovering
I don't think investors are really – I mean, we don't know what the learning rate would be. With a 6% learning rate, even there you see, significant cost declines for smaller reactors because it just costs much less to build more of them. So you still see costs come down pretty fast.

And if you're starting at not so high of a first-of-a-kind cost like 6700, even with a 6% learning rate they come down pretty fast. But also, they are looking at – the reason they're looking at niche markets is because they are already cost-competitive with their first-of-a-kind cost. So for an investor, if you're going to be making money on your very first demonstration reactor that's a lot different than having to wait to build 100 units before your breakeven.

For example, with large wide-body aircraft – Boeing and Airbus – they needed to build a few 100 aircrafts before they actually breakeven on cost, they are selling them at a loss. It's possible that Airbus for their latest wide-body aircraft actually never broke-even, they never got down the cost.

But with microreactors, you can start with niche markets where you are cost-competitive from the very first unit and then, as you come down the learning curve, you open up to new markets. So eventually, you might reach states that have higher electricity costs like California, like Hawaii, and then you might, if you keep building, get down to where you are quite competitive in more places.

So even with that 6% earning rate – yes.

And there are a lot of investors already investing in microreactors, particularly because just the total cost of a unit is so small, even if it's very expensive per kilowatt, it's only 1 megawatt. So, a few million dollars isn't that much for an investor.

Berta Oates
Thank you. Recognizing that standardization is economically critical, how are we going to down-select on what small or microreactor technology will be commercialized?

Jessica Lovering
The big question I have about this question is who is 'We' who is doing the down-selection? I think it's going to be or it should be a little more left up to market. So I think you want to have a good commercialization ecosystem to help more technologies get their licensing. But right now we are seeing several companies start licensing in the US. Two have already submitted.

NuScale submitted a design review and Oklo submitted a combined operating license. I think we are going to see a lot more of those in the next 5 years. And then we'll just see what the cost comes out to be, what the performance looks like for these different demonstrations, and that's how it will be decided. So based on performance and cost, who can build out their order book, who can get more customers lined up, and that's how not we but customers are going to be selecting which SMRs and which microreactors will be successful.

I think for what's been commercialized, we're not really seeing a down-selection. We are seeing a lot of different technologies. Over 60 advanced reactor companies in the US are kind of all working towards commercialization. I think it's good to have that diversity because we really don't know what the market wants, and that's been a challenge in the past when you've had commercialization efforts focused at national labs and through governments as they pick one technology, put all their eggs in that basket, and then there isn't a market for it, or it doesn't actually meet the needs of utilities.

And so, instead building out more of this definitely needs to have strong government support for that technological development but it's more on the infrastructure side. So building out testing facilities, licensing capabilities, to help more companies get through to fully commercially available but then it's going to be competition for customers.

Berta Oates
Great, thank you. Since electric market is so competitive, should nuclear reactor focus more on meeting industries' thermal needs and co-produce electricity?

Jessica Lovering
Yeah, it's definitely something that is being looked at and I actually in the latter two case studies that I did, I have thermal demand data. So I looked at combined heat and power. The more revenue streams you have, the easier it is to be commercially viable.

You do see a lot of these reactor developers looking at code-generation whether it's heat for industrial applications. There's a lot of vendors looking at that, particularly high-temperature gas-cooled reactors and molten salt reactors. You are also looking at hydrogen production and desalination to some extent.

The other one that is really important from a utility perspective is grid services. Things like having peaking capabilities, onsite storage, which we are seeing in some of the molten salt designs, being able to offer more complex services to the grid rather than just kilowatt hours, is becoming more attractive especially when we have more variable renewables on the grid and more concerned about reliability and resiliency.

Again, this is where they are having a diversity of design, so different reactors are going to make sense in different markets. Industrial users might want something different than an off-grid community of 2000 people.

Berta Oates
Thank you. Any rough numbers on how much nuclear capacity would need to be installed to replace diesel generator-dependent communities in Canada?

Jessica Lovering
I could give you that number. The total market is not huge in – adding up most of those communities are quite small. I think it's less than a few 100 megawatts. That's a lot of 1-megawatt reactors but the total market size is not that big.

Another big off-grid market is Australia. They have a – it's kind of like an archipelago of microgrids. They have a lot of off-grid communities as well.

Worldwide it's much larger of course. But for this niche market, Canada is really attractive to a lot of these developers because they pay such high costs for electricity right now.

Berta Oates
Thank you. Regarding learning rates, do you think a one-size-fits-all model is too simplistic as learning rates vary by technical discipline? Easier for a high learning rate control say than vessel manufacture. Also learning rates are factory site plus country-dependent. How well [Unclear] the investor?

Jessica Lovering
I think learning rates depend on a lot of different things. Technology of course, but also how innovation is handled and how changes in designer handled, how regulation is handled? Do you have to submit a new license every time you change one little thing?

That's why I highlighted on the last slide that paper that talks about how policy affects learning rates. That paper was looking at energy technologies but there's some good case studies on how learning rates for things like wind turbines differ in different countries because of the policies they have in place.

I think there's a lot more that we can learn from different energy technologies. But definitely from an investor perspective you want to make sure that you are able to take advantage of learning and not sort of locked into a design that you can't change.

There's a tradeoff between standardization and ability to innovate. And we've seen this more recently, things like commercial spacecraft. There's definitely benefits standardization but you also want to be able to change the design when you learn because that can also bring the cost down through innovation, not just through getting better at processes in your in your factory fabrication.

Berta Oates
Great, thank you. The newcomer countries that are looking to deploy large nuclear plants as baseload sources alongside renewables, how we avoid the challenge of the duck curve and the costs associated with overcapacity during the day?

Jessica Lovering
Okay that's a complicated question. I there's a couple of challenges there. One, countries that are looking at large nuclear, there's not as many but there definitely are a few dozen countries that are looking at importing large nuclear reactors.

Nuclear is not a huge share of their electric grid right now. I mean, their first plant wouldn't be a huge share of their electric grid. Depends on the country of course. And then, they also don't have very high renewables' penetration in a lot of these places. If you have a specific country in mind, ask the question again. I have spent a lot of time looking at the potential for nuclear in sub-Saharan Africa and Southeast Asia. But right now, for countries that are looking at building their first large nuclear, plant that is almost entirely going to new demand, so they would be growing their total electricity generation. And for most of these places, they don't have a huge set of renewables in place; it's more fossil fuels that they are complementing, or hydro which is which is easier to complement.

Duck curve, I think that's a very separate question. That's oversupply of solar at certain times of day and undersupply at other times of day and eating into the peak demand. There are some good studies looking at load falling with nuclear even for larger reactors on large grids and there are benefits to load following even with existing nuclear on large grids. So email me and I can share that with you.

Berta Oates
Thank you. The US has been taking back fuel from research and test reactors. Can this be a model for a US takeback program?

Jessica Lovering
Yeah, definitely. I don't know what more to say about that. It's different because research reactors are much different and the field is much different. But it's definitely something we can do. Historically, the US was the dominant exporter fuel as well. So it's not impossible for us to get there again.

I think something more likely is building out a more diverse fuel supply, more internationalized fuel supply where you have more diversity and who you can buy fuel from, but also having the US be able to offer fuel take-back services is really important and so finding easier ways to do that or incentivize that policy-wise could be very helpful.

Berta Oates
Thank you. How important to these costing models is the relative need for an onsite civil works for microreactors versus SMRs versus LWRs, etcetera?

Jessica Lovering
That's built into the capital cost assumption. I am assuming sort of like the infrastructure that needs to be in place or the construction needs to be done before the reactor comes. I am not quite sure what the source question is, but a lot of the microreactors are going more with a model of kind of plug-and-play. So very minimal onsite infrastructure is needed. Some of these are below-grade, some of these are above-grade, so it's different. Whereas,

you also see a big diversity again in SMRs. So, some are being designed to be deployed in multi-unit packs like NuScale. That has of course a lot more infrastructure that needs to be built before the reactors come. But again, it's this diversity question. We are not sure what's going to make the most sense, and it's also going to be different for different communities.

A community of a few thousand people, they want something really easy that just gets delivered and you plug-in like it is with generators. So they are going to want something with much less infrastructure needed to be built ahead of time. Whereas, a town that's looking to replace its large coal plant might already have a brownfield site where they can do a lot of that preparatory work for a large set of SMRs, so it really depends on the on the customer.

Berta Oates
Great, thank you. What fuel form was assumed – did you look at what most of all of us are talking, like the TRISO or the HALEU?

Jessica Lovering
Yeah. I looked at HALEU for this modeling because I was sort of basing this – although I did a generic 1-megawatt reactor, some of the parameters are based on Oklo because they've submitted an operating license, so there's more information available from them. But I tried to keep it pretty generic, so I looked at a range of uranium prices, a big range to kind of capture all the uncertainty there.

But fuel, even if you double the cost, quadruple the cost, it's not a big component of the levelized costs for nuclear. But I did play with a big range of costs for the fuel. It doesn't matter so much what the fuel is in this modeling because it's mostly an economic model, although there is performance factors in there I recognize, but I did assume HALEU fuel.

Berta Oates
Okay. Is there differentiation in the reliability of operation for different generators? If so, how can this be quantified for micronuclear generators?

Jessica Lovering
I am not sure if they mean different nuclear generators or different fuels comparing nuclear with fossil, there's definitely differences in reliability. There are parameters in the HOMER model that you can adjust, and I did play with, so things like required operating reserve, minimum operating power, ramp rates, those sorts of factors I did play with for the micro reactor.

Nuclear has advantages there but right now if you are doing 100% nuclear, you do have to do load-following of course but you can do it with – oh, sorry, it's still before 7:00 in the morning for me – what is the word I am looking for, steam bypass. The very like simple answer is you can just do steam bypass if you need to do really fast load-following and that's what some of these microreactor developers are looking at doing rather than complicated maneuvering or power cycling for microreactors.

So there are definitely benefits in terms of reliability for nuclear and that's also why Canada has been so interested in SMRs is because delivery of diesel fuel was actually really challenging in a lot of these places. It gets delivered by truck or by boat, sometimes even by airplane, and that can be really hard if there's a storm. And so having an onsite generator that needs to be refilled every 10 years is really attractive.

And that's something that's very unique to nuclear, and why it's being pursued in these places.

Berta Oates
Thank you. There is some clarification on that previous question regarding the scenario modeling. There could be some endogenous and exogenous variables. Sometimes the optimization models are forced with exogenous variables to make them more realistic to avoid the results like you got in the first scenario, low-cost, so zero carbon with no nuclear. My question was related to this. There are some nuclear capacity modeled as endogenous, but please ignore if I still sound confusing.

Jessica Lovering
Yes, I'm not sure what they mean by that. The way HOMER works is it's not a very complicated model. You say, 'Okay, here's the demand for every hour of the year. You can build diesel, you can build nuclear, you can build batteries, you can build wind and solar, try every combination of those, and tell me what's the lowest cost option that meets demand with a certain margin like 25% reserve or something.'

HOMER, when I say it's not complicated, it really just tries every combination. It tries four microreactors and three, and it tries 10 wind turbines and it tries zero wind turbines, and every sort of possible mix. It has a searching algorithm, so it's not just throwing darts but it does sort of try a bunch of different combinations and just see what's cheapest to meet the hourly demand. I hope that answers your question.

The reason it does this huge overbuild for the 100% renewable scenario is that there are certain hours in the winter where the demand is 3.6 megawatts. And from the weather data and from the renewable resource data that HOMER includes, there's not a lot of wind there, there's really no solar there, it's very cold, so batteries have trouble, so it has to build a lot of wind to meet that demanded in that cold winter night. So that's why there's that big overbuild and over-generations.

Berta Oates
Thank you for taking that clarification, and if you guys have ongoing discussion, the email for Dr. Lovering is on that introductory slide, and I would invite you to continue the discussion offline.

Do you think the current licensing model for the US NRC – assuming the US licenses these microreactors – will allow for rapid deportation of these reactors with site permit and whatnot? If not, do you think Part 53 development will improve this?

Jessica Lovering
I'd say yes to both. I think right now with the current license instructor that's in place, microreactor developers are being kind of creative and sort of pushing for flexibility in existing regulations. It's kind of working within the system that we have now to get these first demonstrations built. And it looks like the NRC is willing to be flexible and willing to hear their arguments on these but that's not going to work for mass deployment.

I think also the Part 53, which is in development, a new system for licensing non-light-water reactors is going to be really important as well, and it's important to make sure we get that right. There are lots of people helping with that right now. There's going to be people-building in the current system, and people-licensing under Part 53.

Berta Oates
Great, thank you. Probably, somewhat related. For microreactors, what's the magnitude and impact of regulatory costs?

Jessica Lovering
It can be quite large right now because a lot of the fee structure is based on reactor rather than megawatts. So there have been some modernization efforts in recent legislation to scale regulatory costs more towards size of reactors. But it is a big burden for these companies, particularly the first-of-a-kind or the first companies to go through licensing are paying a big sort of cost premium to get their designs through first.

That's something that future legislation can help with in helping fund NRC in a way that supports developers, so funding it more like how our federal Food and Drug Administration is funded and recognizing the importance of innovation for the general public and funding the regulatory agency for that.

Right now because the NRC is mostly fee-based, it's really a burden on the developer. But that is changing slowly with recent legislation, NEMA, and that's passed. So yeah, there could be more done but we've seen some good progress already.

Berta Oates

Great, thank you. Which is faster deployments, although your type reactors, type microreactor or non-water coolant type? Among the many SMR concepts, which SMR or do you think will be the fastest commercial operation?

Jessica Lovering
I think it's going to be different for SMRs and microreactors. There is really not a microreactor that's a light-water reactor. They are mostly going for non-light-water reactors for the under 10-megawatt range. You do see some that are scaled down kind of SMR but I don't think those are going to be the first to be built.

I think for SMRs you'll probably see light-water reactors first just because regulators have a lot more experience with light-water reactors, supply chain is much better for light-water reactors, so I think in a lot of countries, not just the US, but Russia and China are going to see light-water reactor SMRs first. But there are unique benefits in terms of size and density and core lifetime from non-light-water reactor designs that could be attractive.

So yeah, I think it's going to be a non-light-water reactor for microreactor and probably a light-water reactor for an SMR, first.

Berta Oates
Okay. Will microreactors likely be deployed as standalone facilities or clustered together at a facility?

Jessica Lovering
Depends on the customer. I think you are going to have a diversity and that's what's nice about them. You see this with batteries of course, and I think you'll see the same thing with microreactors.

For these case studies that I looked at for the larger community in Canada, it deploys 3 or 4 units. And an important thing there is that you want to have some redundancy. Having your entire community depend on the one microreactor is dangerous because what if it needs to be shut down for maintenance. And if you are off-grid, that doesn't make sense.

So, I think you'll definitely see a mix even if it's not multiple microreactors. You might see reactor plus diesel or multiple microreactors. And I think for certain industrial applications, see like one microreactor come online and then they can add on to it as their need grows or as they get more comfortable with the technology.

If you are currently operating with diesel or natural gas, you can kind of slowly replace your capacity with nuclear as your diesel generators reach the end of their life or as you find financing. That's a much more attractive model. I think for commercial enterprises and industrial enterprises, if they can slowly replace their generators rather than have to make this big upfront investment in the switchover.

Berta Oates
Wow! I don't even know what else I can say besides wow, what a fantastic Q&A session, and thank you so much for such wonderful discussion.

I will have to go back and look but I think the number of questions and the level of engagement is record-breaking for your presentation. And I can't thank you enough for sharing your expertise, and time with us today. And thanks to the participants who hung on through a fabulous discussion. 8 o'clock my time. Yeah, we've definitely taken out time and I can't thank you enough.

Jessica Lovering
Yeah, thank you so much.

Berta Oates
You are dealing with something that I think people will definitely look forward to as a newcomer into the industry, and the winner of a 'Pitch your Ph.D.' competition. Holy cow, mark down Dr. Lovering's name and watch for her works coming because I think you can tell that this is will be the voice in the industry to come.

Jessica Lovering
Oh, thank you so much and thank you for all the wonderful questions. And I do encourage people to email me if they more or if they want to talk further.

Berta Oates
Thank you everyone, bye-bye.

END