Estimating Costs of Gen IV Systems
Dr. Geoffrey Rothwell, OECD / NEA, France

Berta Oates
Welcome everyone. We're just getting ready to start the next GEN IV International Forum Webinar presentation. Today's presentation is on 'Estimating Costs of GEN IV Systems.'

Before we get started, I do want to take care of some housekeeping-type information. The audio should be broadcasting over your computer speakers. There is a Q&A pod where you can type in your questions for the presenter as those occur to you during the presentation. We will take the question at the end and we will field as many questions as we have time for.

In the file pod, just below that there is the PDF slide deck of today's presentation, which will allow you to click and download that directly to your computer. And last and certainly not least, in the note pod there is a link to a survey related to today's presentation. We do take your comments and your feedback seriously. We genuinely appreciate the feedback so that we can continue learning and improving these webinar presentations. So if you'll take a few minutes and click that link and provide us your feedback, it is very much appreciated.

Today's introduction is given by Dr. Patricia Paviet. Patricia is the Director of the Office of Materials and Chemical Technologies at Department of Energy in the Office of Nuclear Energy. She's also the Chair of the GIF Education and Training Workforce.

Patricia?

Patricia Paviet
Yes. Thank you so much, Berta.

Good morning everybody. It's my pleasure today to introduce Dr. Geoffrey Rothwell. Since 2013, he has been the Principal Economist of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development in Paris, France, where he acts as the Secretariat for the Economic Modelling Working Group for which he wrote the Terms of Reference in 2003 as the Chair of the Economics Cross-cut Group of the Generation IV Roadmap Committee.

He was active in writing the Cost Estimating Guidelines for Generation IV Nuclear Energy Systems. While teaching at Stanford University from 1986-2013, he consulted several US national laboratories: Idaho, Lawrence Livermore, Oak Ridge, Pacific Northwest, and Argonne National Laboratories, for whom he updated the University of Chicago's 2004 report, ‘The Economic Future of Nuclear Power,’ which is published as ‘The Economics of Nuclear Power,’ Routledge, London, 2016.

Dr. Rothwell grew up in Richland, Washington, and received his Ph.D. in economics from the University of California, Berkeley.

So Geoffrey, thank you so much again for volunteering to give this webinar, and I give you the floor. Thank you, Geoffrey.

Geoffrey Rothwell
Thank you. Can you hear me okay? I hope so.

Now. I'm not going to read these slides. Some of the slides are there for background and you can click on the little box in files and download the file and look at the references. So, this is an introduction to nuclear power plant cost estimation. And if I misspeak and you don't understand something, you can put the question in the chat box in the lower right-hand corner.

I am going to give you some history as to how these cost-estimating guidelines and spreadsheets were developed, and then we are going to spend the rest of the talk looking at the Levelized Unit Energy Cost, which most of you know as the Levelized Cost of Electricity, LCOE. We decided to use the Levelized Unit Energy Cost to emphasize the other products such as decentralization, hydrogen production, and so forth that Generation IV reactors could be able to produce.

The Economic Modelling Working Group prepared a Code of Accounts, COA, which is actually used quite a bit now. It is a combination of various codes of accounts that have been previously done in the United States and at the International Atomic Energy Agency.

And so the first thing we need to do to calculate the Levelized Cost of Electricity – I am just going to use the term ‘Levelized Cost,’ instead of LUEC or LCOE. The first thing we need to do to estimate Levelized Cost is calculate or estimate Overnight Costs plus Contingency plus Interest During Construction. And that is going to total up to Total Capital Investment Cost, TCIC, which the amount of money that's at risk when the plant starts up.

The next step is to determine Annual Fuel and O&M Costs, including Decommissioning funds set aside, and we'll be using an annualized model. You'll find out there that there are cash flow models, which we'll talk about towards the end of the presentation, where you can have expenditures in each month over the lifetime and construction period of the plant. We are trying to do here a simple version that anybody can use in estimating the cost of electricity from a nuclear power plant.

And then finally, I will discuss our recent benchmarking between our spreadsheet, G4ECONS with the IAEA's spreadsheet Nuclear Energy System Test, NEST models.

The Roadmap Committee ended up picking six reactor types to organize working groups to share research and development. So, I need to emphasize, the Generation IV International Forum is a process, it's not a product. These reactors here are products but it's up to the member countries to develop, demonstrate, commercialized the products. And the Generation IV International Forum provides a forum in which the research and development can take place so there isn't a lot of overlapping research and development.

I will be discussing primarily an estimate for a molten salt reactor with pebble-bed fuel. And you can see there's many other reactor types being developed by Generation IV International Forum.

So we were on the Evaluation Methodology Group from 2001 to 2003 and we were tasked with evaluating 80 different variants of nuclear energy systems and to select the most promising ones. And the EMWG developed four sets of criteria related to safety, economics, sustainability, non-proliferation, and physical protection.

The economic goals were to have a clear lifecycle cost-advantage over other energy sources and to have a level of financial risk compared to other energy products.

The Economic Cross-Cut Group grew out of the Evaluation Methodology Group and inside that group we had to come up with metrics to evaluate the economics of the various nuclear energy systems. And it came down to two criteria. One was low total capital investment cost, TCIC, the second was low average cost as measured by Levelized Unit Energy Cost. Now, these are called Levelized Cost of Electricity if there is no other products besides electricity being generated. And later, we'll be looking at Levelized Cost of Electricity from the. Nuclear Energy Agency, International Energy Agency, Projected Cost of Generating Electricity from 2015.

The first product was Cost Estimating Guidelines for Generation IV Nuclear Energy Systems and there you have a – I'm not quite sure if it's live on the – it doesn't appear to be live. So you need to take this, copy it and paste into your browser. The last time I did this it popped up – these are the estimating guidelines and they define a Code of Accounts.

The Code of Accounts is a way of defining almost as precisely as we can, what a cost is. There are many costs and so we'll be looking at the Code of Accounts from a one digit, which is 1 through 9, followed by zero; a two digit, which would be something like 21, 22, 23, 24, 25.

And then, we'll be looking at a document that applies the Code of Accounts to estimating a molten salt reactor at the three digit level. And so, we came up with this Code of Accounts to minimize data requirements to be applicable to all Generations IV International Forum member countries to use a spreadsheet where the formulas could be visible, and to allow the incorporation of the modules, in particular to evaluate different fuel cycles.

And so this is here the User's Manual for the Generation IV ECONS spreadsheet, which is available by emailing me and asking me for a copy. Right now, to help keep track of the users of G4ECONS, we would like you to email us and so we can keep you in our database to send you the next version, which is available now, Version 3.0 is available now but the User's Manual has not been completed. And so until we get the User's Manual completed, we aren't distributing Version 3.0.

So the Levelized Unit Energy Cost, we're going to use ‘KC’ to represent Capital Cost and that is equal to the payments each year to the banks and investors and it is to pay down the principle and interest on Total Capital Investment Cost. And so it's as if the electric utility that operates the plant has taken out a mortgage and they have mortgage payments every month. We are going to assume that these can be paid on an annual basis. But in reality, they pay them every month. Just like anybody who owns a home and pays the bank every month, this KC, Capital Cost is the mortgage payment.

And then there's upkeep on the plant and that upkeep is known as Operations and Maintenance, O&M, and Capital Additions which are upgrades or a replacement of equipment, and fuel costs. And the fuel cost is a function of the amount of fuel and the price of fuel. So we are going to come up with an annual payment that the utility makes, the Capital O&M, which is primarily labor, and fuel, and we're going to divide by the sum of the annual energy output ‘E’ and we are going to measure this in megawatt hours and that's going to be equal to the size of the plant in megawatts, the total number of hours in the year, and the Capacity Factor.

So when you see an italic, italic like ‘CF,’ this means that that is a variable and these are parameters. So the size of the plant doesn't really change much over time although sometimes you can upgrade the plant and the size can change. And so generally, we would have to change the size of the plant in the calculation going forward.

The number of hours per year doesn't change too much but there are those leap years. And so we generally use 365.25 days – 365 days plus one 1/4 day – as the total number of hours in a year. And the capacity factor is, how much electricity is being generated as a function of the size of the plant. So, 90% capacity factor means that 90% of the power that could be generated is generated and so that varies from year to year.

Now the GIF Code of Accounts – basically, here we have when it says, 'Account 10 – Capitalized Pre-Construction Costs' those are the costs that are associated with preparing the site. And in general, the site could take 5 years to prepare. There are a number of environmental tests that have to be done over time. And so in general when we say, 'The plant takes 5 years to build' it's 5 years where there is the most money being spent. So you'll see lots of different definitions of how long it takes a plant to be built. And the definition that is used by the IAEA is, 'The plant construction starts with pouring of the basemat concrete.'

So up to that point this would be considered pre-construction costs. After that point, things get more and more expensive and there is a time value of those funds. So you'd like to finish it as soon as possible. And so we need to consider the cost of capital during construction and that will be a term called 'interest during construction,' although it's not just interest, it's also return to the investor, including the utility itself.

The utility will be putting up funds of its own that it could have distributed to shareholders, or to the ministry if it's a government-owned facility. And instead, is putting those into the plant and it needs to earn a rate of return on those funds. We are gonna call that 'interest' but it's not interest. 'Interest' refers to what is borrowed from the bank, the cost of borrowing money from the bank. And so we'll get into that later.

So Account 10 and Account 20 are Direct Costs. And then we add in, field indirect costs, and then we add in, field management costs. That gives us a base construction cost. But the owner is also spending money. A lot of what that owner spends is on the fees to license the site and we can add in a lot of different owner's costs. But generally, when estimating Generation IV nuclear energy system costs, we put the licensing fee in the capitalized owner's operations.

Account 50 is Capitalized Supplementary Costs. Now, many light-water reactors don't have a lot of supplementary costs. But in the Canadian pressurized heavy-water reactor, heavy water would go into supplementary costs. And then we have Capitalized Financial Costs, which are known as 'Interest during Construction.' Each one of these accounts, the second digit of 9, so 19, 29, 39, 49, 59, 69 are contingencies and so we need to add in contingency.

We're going to annualize the capital costs and add to that annualized fuel costs and annualized O&M costs, divide by annual megawatt hours to get a Levelized Unit Energy Cost. Now, generally we use dollars but don't be offended, we can use the euro or yen or Swazi [ph] or whatever.

So here we've broken down now the Account 20 into structures and improvements. And that's buildings. Reactor equipment is what we call the 'nuclear island.' And then we have turbine generator equipment, which generates electricity and cools the turbine. And then that is passed through the electrical equipment and into the distribution grid at what we call the 'bus bar.' And most of these costs are inside the bus bar. So we're not going to be discussing the cost in the transmission system to the consumer.

And then we have a cooling system, which can be cooling towers, it can be the ocean, a river, there's miscellaneous equipment, and special materials such as, sodium in fast-reactors. Base construction cost includes the capitalized indirect services costs which are on- and offsite design and project management costs. We've got the owner's costs, which we discussed.

Now, here's a tricky one. The initial fuel core. In some models, that initial fuel core is levelized over the lifetime of the plant. We included it in the total capital investment cost because to get the plant started you have to have a fairly expensive initial core, and you are going to be using that for several years. But you have to pay for it upfront unless you've got some deal with a fuel fabricator that allows you to amortize that. If you are amortizing that, then it will become a part of annual fuel costs.

So there's interest during construction, which we'll talk about soon, and the various contingency. And these add up again, to the Total Capital Investment Costs. Again, we are going to annualize the various costs and we'll look at examples of each of these annualized costs in the remainder of this presentation.

So here is an example where Oak Ridge National Laboratory used the cost estimating guidelines and G4ECONS available to everyone to write the Advanced High Temperature Reactor Systems and Economic Analysis and you could find that by putting in ORNL/TM-2011/364 into your browser and it will take you to this report. And this is what I consider to be the example of how to estimate the cost of a plant that has never been built, which most of the Generation IV reactors have never been built.

This is the molten salt reactor using a pebble-bed fuel form, which is similar to having a steely marble. If you've ever played marbles, the steely marble was sort of the prized possession of every marble player. And that is, there's a 'steely' of uranium and that's surrounded by different ceramics. And the size of the pebble is just enough so that there is fission without a fusion explosion. Those pebbles come through the reactor and are replaced.

So this is a molten salt pebble-bed reactor. And what. Oak Ridge did was take a two-unit PWR-12 – and this is similar to Watts Bar 1 and 2. Watts Bar 1 was finished in 1996, and Watts Bar 2 was finished in 2016, and their combined size was 3400 megawatts. The cost of Watts Bar 2 according to World Nuclear News was $4.5 billion. And when you divide by the size of the plant, 1168, you get $3850 per kilowatt.

So here we have an example taken from this. You can click on, copy this into your browser and it will take you to this report. The report was done in 2011 dollars and it's preferred by economists to always use dollars of a particular year.

Now, taxes are determined on income that changes from year-to-year. And so if you want to do a precise modeling of a power plant or power technology that does not yet exist, you would use the cash flow model with costs that are increasing over time. And so you need to have some idea of cost escalation.

Now, I've taken their estimates in 2011 dollars and updated them to 2016 dollars when Watts Bar 2 was completed. And you'll see that lo and behold, the price per kilowatt is approximately $3820, which is pretty close to what the cost of Wats Bar 2 was. So you can consider this as an estimate of a Watts Bar 2 plant.

Now, we have to consider the time value of money. I tried to minimize the number of equations here. But what's going on is, you have an overnight cost. And in each period you are going to spend some of that overnight cost and you want to discount to the time when the plant goes online and we're going to call that time 'zero.' And we're going to go back in time to the beginning of basically the pouring of concrete. And that is the lead time.

So we're going to go back in time, so those would be negative years, and we're going to pay it every month, or we're going to calculate every month how much money we have borrowed and on that money that we've borrowed, we have to pay interest. We don't get it for free. And so, the monthly interest rate is related to the annual discount rate, which we'll talk about in a moment. And so actually the calculation of IDC is done in many different ways.

In the G4ECONS, it's approximated with quarterly payments and a so-called 'S-curve' – which looks like kind of like an S – cumulative expenditure distribution. Now, you can simplify this by assuming that this is just equal to 1 over the number of months, and you get a uniform expenditure rate instead of an S-curve.

Now, we're getting into some of the trickier stuff here. The weighted average cost of capital to calculate interest during construction is a weighted average. And the weights are the amount of debt divided by debt plus equity and the amount of equity divided by debt plus equity. And so you are going to have a rate on debt, which is determined by the banks, and your credit rating, and you are going to get a rate on equity that you're going to be paying your shareholders and yourself, the electric utility could be putting in millions of dollars per year from its revenues.

And these are going to be real rates. ‘Real’ means that we've taken out the inflation. And so here, I am going to represent a nominal rate. But these are the things you actually see. This is the rate that you see on your credit card statement. And so I'm going to put a little underline under that for nominal rates, and then we're going to have to calculate either looking at current inflation or past inflation, to take out and calculate what the real rate is.

So we don't really know the real rate. We know the nominal rate and we're going to estimate the real rate by looking at what inflation has been. And you'll see that if the real rate is 3%, and we have a 2% inflation rate, then here's the formula as we're supposed to use it. But generally, we just use this one which is the 5 is equal to the 2% plus the 3%. And usually, if these numbers are small, the error which is 0.06% is going to be small. If inflation balloons as it did in the late 1970s, then this simplification breaks down.

In general, rather than trying to estimate the real cost of capital facing a particular utility in a particular country for a particular project, we're going to do sensitivity analysis using different real discount rates of 3%, 5%, 7.5% and 10% and we'll see how that later affects the Levelized Cost of Electricity. Because nuclear power is so capital intensive, the cost of capital or the weighted average cost of capital, has a huge influence on the cost estimate.

Connection lost! Oh, boy. I guess, you can still hear me. I am rebooting.

Berta Oates
Dr. Rothwell, if you have a hard copy in front of you, I can advance the slides because the image is still seen, at least on my end.

Geoffrey Rothwell
Okay. I'll go to my – well, I am rebooting. This has happened in our – oh, well, we're back to where we started.

Okay, so this is an important thing. If you don't get anything out of this talk besides this, this will be a worthwhile endeavor of listening to me talk, without seeing my lips move.

Inflation refers – this is from an economics point of view – inflation refers to changes in the value of currency and it is measured by doing surveys of ‘baskets’ of goods over time. And so for the ‘basket’ of goods for consumers, it's called the ‘Consumer Price Index,’ and for firms it's called the ‘Producer Price Index.’

There are many different measures of inflation and so it is different from cost escalation, which generally is nominal, i.e., it doesn't include the real inflation rate. And it refers to changes in prices in specific industries such as the construction industry, not generally adjusted for currency inflation.

So the real cost escalation subtracts the currency inflation and there is a common mistake of using cost escalators to deflate prices of construction. And the real way of doing that or the recommended way of doing that is to first put all your dollars or yen or euro or ruble, or whatever, into a constant year, and that gets rid of the inflation, and then to use a real cost escalation rate.

You should not be using a real cost escalation rate to deflate prices of nuclear power plants. Because basically each item in a nuclear power plant has a different cost escalation. And so you want to get the currency inflation done and then figure out what your cost escalators are.

The next thing we need to add is the contingency rate, and it depends on the level of product definition. So here is the Association for the Advancement of Cost Engineering, and you'll see that it is international – you'll see that AACEI, where the ‘I’ stands for ‘International,’ and they basically do a code of accounts for cost engineers. And so inside their code of accounts are guidelines on what rate should be used for contingency.

And so, here is the level of project definition. So concept screening, that was what we were doing in the EMG, the Evaluation Methodology Group, we were screening concepts. And so the level of project definition is zero to 2% and the contingency can be as high as 100%. And so for those, the recommended contingency rate is 50%.

EPRI, the Electric Power Research Institute, also has guidelines but they are not publicly available. You have to be a member of EPRI to get a hold of these guidelines. But I have been told that they haven't changed since 1993. And so EPRI doesn't even give a contingency recommendation for concept screening. A simplified estimate is the equivalent of a feasibility study and the AACE contingency is 30%. So you are going to get your total capital investment cost that includes the 30% contingency on your overnight costs and your interest during construction. And EPRI gives a choice range between 30% and 50%. As the project becomes more defined, then you get lower and lower contingency.

When you are ready to start the construction, you have put out requests for bids on your pieces of equipment and so you should know fairly well what the final cost should be. So it's always a good idea before you start building to have a 100% project definition or you could end up doing some rebuild and getting into delay and so forth.

So if you've got a 100% project definition, then 5% would be the recommended contingency. But we'll see later that not everybody uses this guideline.

Here's an example of different levels of project definition. So the least defined would be the red line and the most defined would be the green line. The red line means, ‘Don't go there’ and the green line means, ‘Go.’ And so you can see I have modeled this as a log-normal distribution, primarily because it can't go below zero. And you'll see that the standard deviation of these samples declines and the confidence that you are going to have in your estimate decreases, or the range decreases as you define your project.

So here we have the Advanced High Temperature Reactor. And what they've done is they've taken this PWR-12, which is similar to Wats Bar 2, and they assume that the pre-capitalized or the pre-construction costs are going to be the same for the two different reactors. That is, site preparation is going to be $6 million regardless of what kind of a reactor you're building.

It’s got two versions of the Advanced High Temperature Reactor – one that uses relatively highly enriched uranium, it is still considered low enriched uranium of 19.75%, and a 9% version. The typical PWR uses 3% to 5%. And so you get the overnight cost without the initial fuel load, which here what they've done is they've taken out systems that they don't need and put in systems they do need that are specific to the molten salt reactor and so without the fuel load.

You'll notice that the fuel load for the PWR is approximately $135 million. For the highly enriched uranium, AHTR, it's over $400 million, and for the 9% enriched uranium it's a little over $100 million. And so, we get the Total Capitalized Investment Cost and then we divide by the size of the plant in megawatts and we get the specific cost per kilowatt electric, which here is approximately $4000 per kilowatt. And they are claiming that the cost is going to be less than the light-water reactor, primarily because their system does not operate under the same pressure as a pressurized water reactor.

Here is an example of Annual Cost for what we call the ‘System 80+.’ System 80+ is based on the System 80, which can be found at Palo Verde, in Arizona. The design was bought by the Koreans and is now being constructed in, for example, Korea and the United Arab Emirates and is known as the ‘APR1400.’

So even though you are not going to see any System 80+’s, you're going to see a bunch of APR, Advance Pressurized Reactor 1400s. And so, on-site staffing costs approximately $32 million etcetera, etcetera. The total O&M cost is $78 million, and then you add in a cost of – you want to put aside at least $2.5 million per year in your decommissioning trust fund and you add that to 78, you divide by the number of megawatts per year, and you get the operating costs are approximately $9 per megawatt hour for the APR1400.

Now to calculate the annual contribution to the Decontamination and Dismantling fund, you use this formula. This is similar to – now, instead of paying off your mortgage, you're saving up to buy a house. And so, this gives you, this is the cost of the house, D&D, and this tells you, how much you have to save per year based on what you are earning in your savings fund.

And you could be earning a lot. For example, in the stock market, right now, if you're in the market, you're earning a lot. But that changes over time and you've got be careful. So this gives you how much you have to put aside each year to come up with the amount that you need to decommission your nuclear power plant at some time in the future.

Fuel costs. I had to put an equations. ‘NU’ is Natural Uranium that has been converted to what is called UF6, which is Uranium hexafluoride. And so natural uranium converted to UF6, there is a price of natural uranium and the price of conversion. And then it is enriched. And what's happening in enrichment is that you're taking out the non-fissile part of the uranium.

So 0.711% of natural uranium is radioactive. The other part is nonradioactive – 99% of uranium is nonreactive. It is that 1% that is needed to increase, for example, in a light-water reactor between 3% to 5% and in this molten salt reactor up to 9% or 19%. And then you have the cost per kilogram of fabricating this enriched uranium into a fuel rod.

Now this cost to determine what the cost per year would be, you take this fuel cost and basically you calculate how much heat you are getting out from that fuel and you are adding a waste cost for the spent nuclear fuel, or if you are going to reprocess it, you put in the reprocessing charges into the waste fund multiply it by the number of megawatts.

And so what this formula is doing is giving you a cost per megawatt of fuel. And again, you can find all this in in my book which – you can email me and I'll just send you a copy. You don't have to buy it.

Okay. Here is the cost for the PWR-12, the AHTR using highly enriched uranium, the AHTR using enriched uranium, and so these are the millions of dollars. This is the FC cost and these are the dollars per megawatt hour. We've gone through these. These are the totals of natural uranium ore. You'll notice that this is about $20 million per year to run a PWR-12, and enrichment is about $11 million a year.

And you divide by the number of megawatts and you get dollars per megawatt. And we're going to use dollars per megawatt instead of such terms as 'mils per kilowatt hour' because it's actually the same value. This is either dollars per megawatt hour or mils, which are thousands of dollars per kilowatt. So we're going to multiply the thousands of a dollar, mil, by 1000 and get a $1. We're going to multiply kilowatt hour by 1000 and get megawatt hours.

And this is the prices that you see in markets. You don't see prices in mils per kilowatt hour. And so the fuel cost for a light-water reactor is about $6 per megawatt hour. It's about $18 for the highly enriched AHTR, Advanced High-Temperature Reactor, and it's about $10 for the lower enriched AHTR.

Now this is a report that is about to be published. We are waiting for an agreement with the IAEA because they would like to also print it. And so it'll be coming out soon and you can check on the NEA website for its release. It was done in collaboration with lots of people, including the International Atomic Energy Agency.

Now, the primary purpose of that report is to calculate employment. And this is a breakdown of these are typical costs for a nuclear power plant in the United States. They are paying approximately $70 million in labor and $20 million in taxes. And this is the North American Industrial Classification System, and what we've done is take each one of these expenditures and put them into a 6-digit industrial classification code. And when you see the report, then we are going to calculate in each one of these industries how much is generally spent on labor.

So we're going to get labor costs and equipment costs and that will give us how much labor is being used to install the equipment, and how much labor is being used to build the equipment.

Now here is a calculation of when we say ‘Levelized Fuel Costs,’ this is the simple version, and this is the actual amount. And so, when we add up all these things that are associated with fuel in the actual amount, we have $37.3 million being spent. When we use the little formula that we saw before and put it in here, here we have the cost of uranium – before it said $20 million, and now we are down to $16.7 million.

And that is because of the fall in the price of uranium. We have to convert that uranium to uranium hexafluoride and enrich it. We saw that they were spending approximately $11 million on enrichment for the PWR-12. And in our typical generic power plant, we are spending $13 million – so a little bit less on uranium, a little bit more on SWU. And then we get a fuel cost, using those formulas that we looked at before, approximately $37.74 million, which is off from $37.3 million by $340,000 which actually for cost estimation is pretty good.

Now, here we have an estimate of the Levelized Costs or dollars per kilowatt hour from the ORNL, 81,000, we get a Total Capital Investment Cost of a System 80+, in 2001 dollars of $2092. The PWR-12 comes in at about $4000 Total Capital Investment Costs.

We saw these before.

Now we're going to compare them to what we found in the Projected Cost of Generating Electricity. And here we have all these components. These are experts from these various countries that gave us information on the size, overnight costs, investment costs which would be Total Capital Investment Costs at 3%, 7% and 10%.

And then on refurbishment during the life of the plant and decontamination and decommissioning, these are the costs at the end of life. So if we earn 3% on the Decommissioning Trust Fund, we have to put away – to pay for a typical Generation III reactor in Belgium, we have to put away $0.50 per megawatt hour and that's accumulating at 3%.

If we're accumulating at 7%, we only have to put away $0.08. And if we're accumulating at 10%, we're getting a 10% return on our decommissioning trust funds, we only have to put away $0.02 per megawatt hour. And then we've got fuel and waste which you will notice is in the ballpark of what we were talking about a couple of slides ago.

And then, the O&M costs, a little bit higher but we still find in Korea they have O&M costs that are approximately what we calculated earlier. And well, lo and behold, this is the APR1400, so it's not surprising that we see that the O&M costs for the generic PWR-12 and System 80+ is approximately $9.65.

Now, in terms of Levelized Costs, you'll notice that as the cost of capital increases, you get the doubling of the Levelized Costs per kilowatt hour. You'll also notice that Korea is coming in with a cost of $2000 per megawatt hour and the Chinese are coming in with an AP1000 at a cost of $2600 a kilowatt hour. And their own version of a generic pressurized water reactor is coming in at $1800 [ph]. So it's no wonder that we keep seeing construction happening in the East.

So we wanted to know if our G4ECONS' spreadsheet was working if we got the same answers as everybody else did. Meghan Moore and Ramesh Sadhankar are on the EMWG, the Economic Modeling Working Group, and Andriy and David are working at the International Atomic Energy Agency. And so we picked a number of reactor types and put in the same cost and we wanted to know if we would get the same output.

So I'm going to skip this. This is the abstract from their article. And here is the important one. They've got four versions of their NEST model. The first version is something that they designed about 10 years ago, and it's good for 'once-through fuel cycles,' which means the fuel goes through once and then is a package for the repository.

The second version is based on the model in what's called Bunn et al., Bunn, Fetter, Holdren, and Van der Zwaan, 'The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel.' That is available online.

Version 3 is a cash flow model that was developed at MIT in 2003 and then used by the University of Chicago in their report in 2004. And you can find that on their 'The Future of Nuclear Power' website.

Version 4 is an extension of Version 1, to allow for closed fuel cycles. Closed fuel cycles imply that you are taking the fuel from the reactor, generally light-water reactor, you are reprocessing it, and using it as fuel in either light-water reactors or in fast reactors.

These are the technologies that were compared. And you can look at the technologies at your leisure. Here is one thing you should know. Advanced Fuel Cycle Cost Basis comes out of Idaho National Laboratory and they are about to release the latest version and there is also an attempt at the International Atomic Energy Agency to take this basically American-oriented Advanced Fuel Cycle Cost Basis and turn it into an International Fuel Cycle Cost Basis. And so in in general, we don't see much difference between the various versions of NEST and G4ECONS.

Here what we've done is break out the different types of costs – enrichment, conversion, uranium. And here is Levelized Unit Average Capital, Levelized Unit Fuel Cost, and Levelized Unit O&M Cost.

Conclusions. Basically, it has to do with what you do with the first core. If the first core is incorporated into the amount of money that you've got to spend before the plant starts generating, then you are going to get a slightly different answer than if you use these models that are available from the International Atomic Energy Agency.

And so with that I would like to point out that the next webinar is on November 29, on the Phenix and Superphenix and these were fast reactors that were built in France in the last century. And so that should be pretty good one. Relevant framework for addressing fuel cycles, and I have introduced you to that. And then we have this HTR, High-Temperature Reactor using these pebbles that the molten salt reactor would be using.

And this reactor, this High-Temperature Reactor, a pebble-bed version is about to start generating electricity in China. And so, this is a very topical presentation and I am sure we'll all join together and doing that webinar.

So thank you for your attention and I am ready to answer questions or entertain you. I can't do song and dance because you are not going to see me dancing. So if you have any questions – I don't see anything in the chat box.

Berta Oates
Okay, Dr. Rothwell, thank you for your presentation.

In the Q&A along the top there's the presenter view tab and a participant view tab, and you are going to want to click it to the presenter view tab. There are a couple of questions in there, the first of which reads, 'Why initial fuel load is cheaper for 9% enriched uranium than for 3%?'

Do you see?

Geoffrey Rothwell
I don't see the question.

Berta Oates
In that pod where it says, 'Q&A'?

Geoffrey Rothwell
Yeah.

Berta Oates
Scroll your mouse over the top.

Geoffrey Rothwell
Q&A? Okay. Okay, I see it. Basically it didn't go down that far. There's a lot of stuff from Reevas Genes.

Okay. So here, this is a fuel rod and these are fuel pebbles. So these are very different. Basically it has to do with enrichment or total cost?

Okay. I am sorry we didn't practice this part of it. Okay. Is the cost…

Oh, my God, where are we?

Berta Oates
Okay. The question is from Edgaras – I apologize, I am going to butcher your name.

Geoffrey Rothwell
Okay, alright.

'Why is the initial fuel load cheaper for the 9% enriched uranium than for 3%?'

Because they are different types of fuel. This fuel is in a fuel rod and these fuel rods are bundled and they've got spacers between the rods and you've got several bundles of fuel rods that are put into the reactor. These are pebbles.

I don't know.

Fuel cost is $9 and $4 for PWR. So why is initial fuel load?

Oh! I see, initial fuel load.

Berta Oates
Slide #18.

Geoffrey Rothwell
Slide #18. Okay. So this is a different type of fuel. These are pebbles that are mass-produced basically by a machine that's compacting the uranium and then putting ceramic over the top of them. And they are continuously refueling. The pebbles are coming through the reactor and coming out of the reactor and then being put back into the reactor and coming back out of the reactor.

So when you're starting up a PWR, this is enriched in general to the level that you need. But you are going to be putting in new fuel. In the first cycle, probably it'll take you 3 years to get through burning the first cycle. These are coming out and going back in. So if you see, the initial fuel load is lower because it's a different type of fuel but the Levelized Fuel Cost is at least twice as much for this highly enriched uranium than it is for this lower enriched uranium.

Now, we've also got a question about backend and here there was an assumption when this was made that $1 per megawatt hour was going into the nuclear waste trust fund and so that was the money – they had collected about $30 billion to build Yucca Mountain and had spent $11.5 billion on Yucca Mountain before it was defunded. And now they are talking about going back and licensing Yucca Mountain.

In the Nuclear Waste Policy Act, basically the government, the US Department of Energy cannot deal with building centralized storage facilities and tell, 'Yucca Mountain is licensed.' So that's the first thing that has to happen is, getting a license for Yucca Mountain. Then they can decide whether or not they are going to build it. But until they have the license, which essentially means it's feasible, they can't do anything else. And so that's why you want to get the license and why we are spending money on getting that license.

Okay. So, is the cost of the final disposal in there?'

And so here we have it here, the storage cost before disposal is approximately according to this calculation. Personally in my own calculations I also put $1 here and so that means that this is $2 for a light-water reactor. So anyway, it's in there. It's a part of the calculation.

'Regarding the SMR approach, how does it impact the LCOE and can it be modeled with the current version of G4ECONS?'

Generally, let's take the NuScale example. In the NuScale example, you have 12 small reactors and six are in one pool and six are in another pool. We can do one reactor at a time. But in G4ECONS, we don't get a fleet of reactors, which is what you would have if you had an SMR, Small Modular Reactor approach. Now, where the SMR comes is in the Interest during Construction.

We are going to assume generally when we are looking at this that the lead time is much shorter for a modular reactor before it starts generating electricity. And that means that there is a lower risk associated with the discount rate. And once we have built a number of them, then we are going to assume that the overnight cost is lower. So that's where we are going to get savings.

We still have to get rulings from the NRC about the emergency planning zone, how much space do we need between the reactor and the public, and the number of control room operators. Right now, you are supposed to have one operator for every reactor, which means that in a NuScale reactor you'd have 12 operators basically sitting side by side. And so, NuScale is trying to get a ruling on whether or not they need 12 or whether these can be – a running reactor doesn't require 12 people sitting side by side. So maybe it's three people in 8-hour shifts and so what's they are.

Okay. Jun Sun, ‘Is there any applications of these cost estimation methods in NPP embarking countries?

Generally, these are being used – this is what the IAEA specializes in and so that's what these various NEST models are available to IAEA member countries and almost all countries are a member of the IAEA. And so, they'll have access to these.

Now, there is infrastructure that needs to be built. So that's why we talk about nuclear energy systems rather than nuclear power plants. Most of these estimations are for nuclear power plants. And so, you need to work with the IAEA in a milestone approach to determine what infrastructure and regulatory system you need and that is going to – if you need to build a transmission line, build a port that can take nuclear fuel, and so forth. That's going to add to the cost of your first nuclear power plant.

And soon, these nuclear power plants will be operating in the United Arab Emirates and we'll have a fairly good idea of what it means to go from zero nuclear power to 4 units in a decade and how many other costs that have been incurred by the UAE.

Okay. ‘Should the first GEN IV reactor pay all the R&D expenditure if no other same reactor is foreseeable to be built?’

Wow! This is a great question

That's why we have the Generation IV International Forum, to help spread these R&D expenditures across countries and not have every country doing the same R&D. So then a more pointed question would be, once you've done the R&D and you are building a prototype or a demonstrator, where does that money come from?

Now, in my own modeling, in my book, you'll see that what I did was I put the cost of the demonstrator reactor over the first eight facilities. That is what we call the ‘first-of-a-kind cost’ not just for the very first one but for basically all of the reactors that are being built that use the demonstration technology.

Actually, research and development is not a big expenditure but demonstration is. And so, that's why we have International Generation IV Forum is to answer that very question.

Here's Ed, ‘Specific power density is a very important factor. My guess is that the power density is much higher in the AHTR unless you have higher thermal efficiency.’

And that is helping to answer the question about advanced high-temperature reactors. Ed Hoffman is one of the world's premier experts on this. What is the basis for the $300 million D&D estimate?

Well, remember, and this isn't my stuff. I would never use $300 million. But basically that is the cost of decontaminating a facility, not dismantling it. There is a formula that the US NRC uses to determine the minimum amount of funding that needs to be put away. And so that is the minimum amount. And personally, I think it's too low but these aren't my estimates.

Generally in G4ECONS, the D&D amount of $300 million is going to be related to the direct cost of the reactor. Here we have capitalized direct costs and these are – let's use the earlier figure, $2 million. And so the $300 million is a fraction of the $200 million. Personally, I think it's too low but in the version of the G4ECONS that I was using…

I can't control the people at Oak Ridge, they are too smart. And so, they came up with this number. That is their number. I don't know where they got this number either! But generally we assume that the cost of decontamination and decommissioning is 1/3rd the cost of the direct cost of building the plant. And so, personally, I think it should be a fraction of the base construction cost rather than a fraction of the decommissioning cost.

But you can download our report from the Nuclear Energy Agency called the ‘Cost of Decommissioning Nuclear Power Plants’ and there will be guidelines on what we should be putting away. Personally, I think you should be taking the decommissioning cost estimate, subtracting what's in the decommissioning waste fund, and dividing by years remaining, and that should be your annual contribution.

I don't think you should assume that you are going to be earning anything on that. Because if you look at the investigation into the decommissioning of San Onofre 1 by the California Public Utilities Commission, they assume that the cost escalation in decommissioning is going to be equal to the return on the fund, and so the real return on the fund is zero. And that's what Finland uses.

Okay. ‘What is the assumed lifespan of the plant in the calculations?’

Generally, we used to use 40 years. And then, a lot of plants in the United States were extended to 60 years. In my own work, I use 50 years or in the publication that's coming out soon I hope, we use 50 years. So there's 50 years of operating jobs.

Okay. Thank you, Mark.

‘In practice, do tax shield conferred by interest charges and amortization play a role on LCOE?’

Okay. Good question! See, we try to make this thing as transparent as possible. And so we did away with consideration of taxes because taxes vary from country to country. But if you ask me for a copy of my book, basically the DOE paid for this, the Department of Energy, US, paid for this and so I'm willing to send it to you.

You'll see that in Chapter 2, there's an appendix, Chapter 2-A, ‘Levelized Cost and the Cost of Capital,’ in which I examine all of the different ways of, for example, financing nuclear power plants, different tax credits, and so forth. And so, you'll see on page 64 in Section 2-A.3 ‘Cost of Capital under Various Policy Instruments’ I examine depreciation rates, production tax credits, investment tax credits.

Basically, this question that is raised by Celestine is associated with the loan guarantees that helped finance the plants that are being constructed in the United States.

And they were able to get up to 80% debt with 20% equity. That would be like you putting down 20% of your money on a house and getting 80% from the bank. Generally, the house is considered to be an asset that the bank can seize from you and so it's willing to finance up to 80%.

In general, Nuclear Power Plants may not be finished and so banks would prefer not to lend up to 80%. But under the Loan Guarantee Program, they were funding under 80% and the 20-year bond rate was the basis on which to calculate the loan guaranteed cost.

And so, you'll see on pages. 66 and 67 what happens under these various assumptions about how much debt and how much equity, debt being something that is basically you are paying the bank and its the bank who is paying the taxes on the payment and so you don't pay – for example, when you're doing your taxes in the United States, you subtract off what you paid in the mortgage and that's because there's an assumption that the bank is going to pay taxes on that. And so that's why you get that tax shield.

Okay. Well, I guess we still have 36 people but we've run out of questions. Let's see. I'm now going to be working this up into an 8-hour version. I did a 7-hour version on Skype with South Africa in 2016 and I am preparing now for a workshop with Chinese engineers on December 11th and 12th and I've got about 12 hours with these people and I'm going to be giving them copies of G4ECONS Version 3, and seeing if they can break it.

And so this presentation is just the first 32 slides of a 132-slide pack that I'm going to be developing in the next 6 weeks. And I will be available or somebody will be available to give future presentations on how to estimate costs from Nuclear Power Plants, which is a fairly complicated problem. And so in my book, I look at probability distributions for all of the major costs and come up with a probability distribution for the Levelized Cost of Electricity.

And so that's where some of us are moving in Levelized Cost space. What's happening is that we are getting ready to update the Projected Cost of Electricity in 2020. This is the 2015 edition. And these are costs projected to 2020. So you'll notice in this that the cost of solar are declining. And according to the International Energy Agency, they are plunging. But that's because these are anticipated costs for 2020, not actual costs.

So in 2020 we'll be doing anticipated costs for 2025 and we need to deal with some of these more complicated issues such as system costs, and we're in the process of finishing a study on system costs. System costs basically are those costs – for example, let's say you have solar. Well, generally, solar doesn't work at night. So you would have to come up with some way of storing solar energy. So you can think of a system cost as the cost of backing up solar at night. Now that could be a battery, it could be a battery in your car, it could be a battery someplace else, it could be pump storage, or it could be a Nuclear Power Plant that is producing power basically 24 hours a day come hell or high water.

These plants – when we had those hurricanes in Texas, those power plants were just pumping out electricity. If Puerto Rico had a Nuclear Power Plant, they would have electricity right now but they don't. And so, these Nuclear Power Plants are now built so they can withstand aircrafts, they can withstand a lot of the natural disasters. And so it's a shame that these plants are being shut down in the face of low gas prices in the United States and in face of subsidized renewable in places like Germany.

So these plants continue to pump out power in many different climate changes and so I don't know if the windmills will survive. There is a photovoltaic PV field that was destroyed in a hailstorm. So, now they have to figure out what to do with the panels which are filled with heavy metals and rare-earth elements. And so now we have to think about the cost of decommissioning these panels and that hasn't been generally put into the cost of PV, solar PV.

So, let's see. I am just talking, telling stories about projected costs of generating electricity. You can download this today and check out these types of tables for all sorts of renewables and all sorts of fossil fuels and so forth.

So I guess unless the remaining 33 of you have questions, I think I am done.

Berta Oates
Thank you, Dr. Rothwell. Thanks everyone for your participation and for participating in an engaging Q&A.

With that I think we'll conclude today's presentation and look forward to next month's GIF webinar.

Thank you.

Patricia Paviet
Thank you, Geoffrey, thank you so much. Bye everybody!

Geoffrey Rothwell
Bonne journée!

Patricia Paviet
Merci.

END