[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: So we looked at the history of nuclear technology and we learned that it was not optimally selected. It's an artifact of the Cold War that we got where we are. We looked at climate change as a motivation for nuclear. And I made this sweeping statement that without climate change, it probably isn't a motivation for nuclear, just because of the prices.

But we found that we can't really quantify the damages from climate change very well. And so we devised this approach, which is to say we're going to look at cost plus externalities, and then have this free parameter for the social cost of carbon, which we can't define even roughly, because of the phenomenology associated with feedbacks and the way the uncertainties spread out. And we show that after 125 years, scientists have not been able to constrain that number any better over the past century.

And indeed, it is itself a time-dependent function that changes as the climate state changes. So we don't know what it should be, but we know that the optimal level isn't 0, because there at some point the marginal cost of abating CO2 is going to exceed the marginal benefit from that abatement. And so there is some level of non-zero CO2, which is optimal in the system. But this is just like a heuristic that we keep in our head, when we think about looking at different things.

We'll use this rough model with the Fried parameter, the social cost of carbon as a free parameter, just to study the phenomenology of the system. We can't possibly get an exact answer, but we can look at what happens if this SCC is low, the SCC is high. How high does it have to be? How much carbon abatement does a certain SCC drive? And what technology makes it supported under a variety of assumptions? And then you can decide for yourself, what you believe. As far as SCC that gives you the technology output that you want, which is what everyone basically does.

But we will try to ground it in thoughtful assessments that have been done by other entities at some point. OK. So to do this computation, we need to be able to compute the first of these terms, which is the cost of energy. And I want to walk you through how to do that in perhaps a little bit more detail than you've experienced before. And to do that, the first thing we need to do is to review the time value of money.

Now this is the effects of interest rates and so on. And you all have seen this back in elementary school. And you all know that an interest rate causes the balance to go up. And you may even remember all the equations, except do you really know what an interest rate, where it comes from and what does it mean?

So I want to try to communicate some philosophical points so that you can have these in your head, so that you can use these numbers in a better-informed way, because it turns out that these numbers, because they appear in the exponent, have an enormous effect on the outcome. And so you can just select the number that gives you the answer you want, which is what everyone does. And that's bad practice. And if you had a better sense of where these things come from, you might do better at this.

So let's just talk about this. Why does the value of money change and why does it matter for nuclear? Well, when you're building projects, they take many years. And so you have to worry about things like inflation. You also have to pay for it somehow. So you usually borrow money and there's a finance charge, and that goes up as the time goes up. You have to pay interest on that. And another thing that we deal with in building power plants is that we spend lots of money on lots of things over lots of different times. And at the end of the day, we have to have one number, which tells us what it cost.

And so we have to find some way of aggregating all of these different streams that happen at different times into a lump sum at a certain time. And so you probably in your head can imagine how you would do this, but we'll just walk through it real fast.

So the first of those was inflation. So why is the value of money change? So it turns out, and I'm not exaggerating here, there's something like 15 different reasons inflation happens. But the basic top ones are shown here. So the first thing is money production. And if you don't know how money is made, I really suggest you go on YouTube and find a video about how money is made, because it's a little weird.

I mean, we could get into it. Basically, it's a process of banks making loans. They create money out of thin air in that process. So go find some video on this, if you're not familiar with the generation of money. I'm not talking about currency. I'm not talking about the US mint printing cash. That's on the balance book. There is so many dollars in circulation in the economy, and it is synthesized by private banks when you take a loan. It's a really interesting phenomenon.

So what happens is, through the process of synthesizing this money via loans, we generate this numerical representation of value in the system. And then there's the real amount of value in the system, which is your labor, and creativity, and your hard work. That's actually generating real economic value. And if these things get out of sync, then the value per unit dollar either goes up or down. And so that is inflation and deflation.

And through monetary policy, we try to keep it the case that inflation always happens. So that the value of the dollar is always going down very slightly. This is to say the amount of money being generated is slightly exceeding the real economic productivity. So that the value per-unit dollar is slowly going down. And someone could probably quickly tell me why that is important.

AUDIENCE: Well, it means you're better off spending money now because it's worth more.

PROFESSOR: Yep, and if you don't have that interest, you don't have that motivation--

AUDIENCE: You can just hoard it and not spend it.

PROFESSOR: You can hoard it, and then the economy shuts down. So this is all about keeping the economy ticking along. So we have to have this inflationary process. So that's one phenomenon. The second phenomenon that we have is that there's some opportunity costs. Right? So I could do various things with my money. And if I decide to lend it to you to build your new tokamak startup, I can't do other things with that. And so I demand some payment for giving you my freedom in a way.

So that is the opportunity cost. And another parameter that I didn't put here, but there's also a risk factor associated with that, which is to say that if your tokamak startup doesn't work, I might not get my money back. And so I have to also have some kind of probabilistic and expectation value, some extra factor that says, in expectation I will get all my money back, plus the opportunity charge that I'm taking in.

AUDIENCE: It's a really dumb question, but you're mentioning banks, but banks really shy away from funding these kind of facilities because the risk is very high. So what happens if I'm a normal investor, and normally VC because then I'm not really lending money, I'm just investing and many times I'm just getting equity.

PROFESSOR: Yeah but you are lending it in the sense you're getting equity as an instrument that you can then sell, you hope, and get your money back. If you just had equity in perpetuity, that would not be interesting. Yeah.

[INTERPOSING VOICES]

AUDIENCE: I don't really see the connection with the bank in the sense like you have Commonwealth Fusion Systems, you don't have any banks in their capital.

PROFESSOR: That's fine. But anyone lending money to anyone through any instrument is basically applying the same rule that if I'm going to invest as a VC in your company, I have to consider all the other things I could do with the money, other investments I could make.

AUDIENCE: Opportunity cost.

PROFESSOR: Opportunity cost plus the risk associated with this particular venture.

AUDIENCE: OK.

PROFESSOR: Right, yeah, so it's all the same kind of phenomenon. Yeah.

All right. And then the third effect is just the pure preference for early consumption. This is a psychological property of humans, which is to say that if I offer you $1 today or $1 tomorrow, most people will prefer to have the dollar today because who knows what will happen tomorrow.

So it turns out that this effect, there's a few assumptions that are baked into this. One assumption is called free storage, which is to say that if I offer you a case of soda, you might not take it because it's not free for you to store. You have to carry this case of soda out of here, put it somewhere until you're done with classes for the day.

OK, so we ignore that we have the assumption of free storage. You can just magically take it, like in video game, you can take an endless number of things you find on these dead characters. And the other phenomenon associated with this is it turns out this is a time-dependent preference.

So economic psychology studies find that people have a reasonable, measurable preference for early consumption when they're talking about today versus tomorrow. But when they're talking about 2028 versus 2030, they're like, that number somehow goes down very rapidly. And so this actually matters. We'll talk about this in a moment. That matters with respect to climate change issues.

So I promised earlier I would talk about the Ramsey rate, which is the social discounting factor. So we're taking a little diversion now away from traditional finance, going back to climate change. And in climate change, we also discount future damages. When we generate an estimate of the social cost of carbon, we say, well, if that damage happens 100 years in the future, it's not the same as if that damage happens right now, and all kinds of reasons why.

And so the Ramsey social discount rate is a way to try to approximate what the discounting factor is. And so it has these three terms. One is the one I just mentioned, the pure preference for early consumption. And a lot of people argue that this number should be approximately zero. And they argue that because they're saying that, look, all future generations should matter as much as our generation and we shouldn't be greedy. So we'll set this number to zero.

Perhaps the better explanation for why this should be close to zero is simply that in psychological studies, when you're looking at long time horizons, this number is approximately zero. So this is small, what rho is, it's small.

The second parameter is a two-part parameter. It's eta times the growth rate. Eta is a unitless parameter, which is the elasticity of marginal utility with consumption. What does that mean? It means this is a measure of the percent change in the usefulness of, let's say, $1 or a usefulness of what they're actually saying is a usefulness of unit of consumption-- burning some coal or natural gas to make some energy-- as the amount you consume goes up, percent change of usefulness as a function of the percent change in the amount that you use up.

So a 1% increase in consumption leads to an eta change in utility. That's the idea. So logically, eta will be negative and it will have the effect of that essentially as your consumption goes up, the utility of that consumption goes down. To put it in another terms, we've all become more Elon Musk like, so the value of an extra dollar means less and less and less to us as we become wealthier.

However, just in terms of science, interest rates are very loosey goosey on signs. You just have to think about it. So generally, this is written as positive. This is positive. And this is technically negative. But then the way they define eta is they put an extra negative in there to make this positive. So it all adds up. So you just have to think about each term in an interest rate and think, OK, should this be positive or negative, and figure out what's going on.

And then g, because g is typically defined as positive, is the growth rate in per-capita consumption. So this is just how much we are getting richer over time.

AUDIENCE: If there is a preference for early consumption, wouldn't money be worth more now than later when right now I want to consume. And so I have a higher demand for whatever I have. So shouldn't rho be something that's somewhat negative?

PROFESSOR: No, because the equation would be that the value at some time t is equal to the initial value times-- so well, it depends on whether you write a minus sign right here, but rho t. Yeah, so it would be negative, it should be negative. But normally you put a minus sign, then it's positive. So it's the same thing. You just have to watch your sign.

AUDIENCE: But it should fall over time?

PROFESSOR: Yeah.

AUDIENCE: The value.

PROFESSOR: Yeah. You just think about it and make sure that all your signs are right. Because there's poor convention in how these things are written out. OK. Yeah. I guess if you call it discounting, then you put the minus sign in that equation, and then all these terms are positive. That's typically the way it works out.

OK. So g is the growth rate. And it's basically a statement of the consumption path that you forecast for society. And so it gets multiplied by eta to change consumption into units of utility. That's the purpose of having eta times g.

The difficulty, there's some difficulty in selecting g though. So if you assume g is greater than zero, you're assuming that people are getting richer, which is generally, the assumption of economists. And if g is less than 0, then people are getting poorer in real terms.

One of the problems, yeah?

AUDIENCE: When we're talking about people getting richer and people getting poorer, is that for the dollar amount or for some equivalent goods amount?

PROFESSOR: We'll say it's in purchasing power parity.

AUDIENCE: OK.

PROFESSOR: So it's dollars that are inflation-adjusted. So one of the problems with trying to pick g is that you have growing inequity in the system. So here is a plot of two terms. This blue line is the real, meaning inflation-adjusted, real median, median meaning we've chosen a measure of central tendency that ignores outliers. Real median household income in the United States, OK, it is going up. But there have been some periods of stagnation.

The dashed green line is the essentially average income per household. It's GDP divided by households. And you can see that that goes up much more steadily. So what describes this divergence between the median and the means in this? It is increasing wealth inequality in the United States, which is to say that most of the gains, which are being represented here in the green line are actually going to the very wealthy.

So as a result, how do we set g? Do we choose g to be a low number because we want the median measure of people's well-being, or do we take the average, and so on? So there's some challenge in setting g. And there are various ways people have attempted to come up with an adjusted value of g. There's something called the Atkinson parameter. I don't exactly remember the name of the thing, which is a way of measuring wealth inequality and trying to come up with a fair g to put in your social discounting factor.

Incidentally, if you're wondering, the color coding, red is when we have a Republican administration in the United States, and blue is when we have a Democratic administration in the United States. Whether there's actually a correlation between these apparent divergences between administration, there's not really statistical power here, let's say. It could be these darker bars are also recessions. Another way to look at it is these divergences tend to appear right before the recessions hit.

This is macroeconomics. We can worry about this later. So real economists tend to put some numbers up around 1% for rho, 2 for eta, and 2 for g, which is a little ambitious because if you go back to this plot, this is 1.5% growth rate and this is 0.75% growth rate. So putting 2 for g strikes me as little ambitious. And putting 1% for rho also strikes me as ambitious. So when I do this, personally, I think this number should be small, close to 0. But the general recommendation of the field is something around 5%. That's generally what people do, 2 times 2 plus 1. Yeah?

AUDIENCE: That's 5% annual, correct?

PROFESSOR: 5% annual. Yeah. That's right. It's a force of interest. We'll talk about that in a moment.

And diversion on climate change and social discounting, so let's go back to finance. All right, so I just want to make sure people have-- you'll run across these terms-- nominal dollars, current dollars, actual dollars, real dollars, constant dollars, year so-and-so dollars. I'll put these slides on the website so you can look at them. You should just know what these are.

Nominal dollars means that the currency has the value in the year that the money was spent. And so when you look in a report, and they said we spent $2 billion on this nuclear plant, that's probably going to be in nominal dollars for the year of the report, unless they particularly say it's in year 2023 or something. Real dollars are inflation-adjusted dollars. They also call this constant dollars.

So all the plots I'm going to show you in this class, almost all the plots will be constant dollars. Everything is inflation-adjusted. So they you can compare dollar at one year to a dollar at another year, and it's a meaningful comparison. So how do you do this inflation ingesting?

It's actually not exactly-- OK. One more set of terminology. So we have the nominal interest rate and the real rate for interest rates on loans. When you go to a bank and you get a loan, the entire loan is written in nominal terms. They ignore the effect of inflation. They write you a contract that says we're going to charge you a certain interest rate, and you're going to pay us back with dollars in the future. And they don't say, but you have to increase the dollars that you pay us back, because the value of the dollar might go down. They say you borrow this much money, you pay the interest and on that end, you pay those back.

And what they do is they suck up the damages from the Inflation that they would bear into the interest rate. So they roll it in. So the interest rate will always be the inflation rate plus, or should always be the inflation rate plus some opportunity cost and risk-adjusted rate on top of that. And that's where the interest rates come from.

However, sometimes when you're working in real dollars, where everything is inflation-adjusted, it's useful to write interest rates in the real rate, which is you take the nominal rate and you just subtract out the inflation rate. So we'll do that, I think, a little bit later in this class. And so this reflects only the opportunity cost and risk of loans, the real rate. So make sure you get those right. Yep?

AUDIENCE: Why is the inflation rate in absolute value terms? And we haven't had this for a long time. But if you presume it's the early 1930s or something when we have a negative inflation rate, wouldn't that be better for banks essentially, in that they're taking in more? I don't get why that's still--

PROFESSOR: So if they wrote a contract and then we had, so that's called deflation. If they wrote a contract alone, and then there was some deflation, yeah, they would benefit from that.

AUDIENCE: Yeah.

PROFESSOR: But on the whole, everything is a market, including capital markets. So let's say we were really in a period of sustained low-grade deflation. That would also get factored in to the lending rate. Because if your loans were more expensive than his loans, then people wouldn't take your loans. So that effect is always going to wash out in the end. Yeah. It just gets rolled into the number at some point. But there's no good or bad.

So how do we do this historically? This is important because you might, we will look at this class, we will look at historical nuclear reactor projects. And we will try to understand what they cost. And we'll need to adjust the time basis of the money. So how do we do that? So if you're looking backwards, we use these indices-- producer price index, consumer price index, and something called the GDP inflator.

And so let me just explain what these are very briefly. CPI is what is normally reported in the news. This is a basket of goods, of everyday goods that typical consumers purchase. It's milk and eggs, and housing, and gasoline for your car, and things like this. And this is an attempt to measure how much inflation is going on, because inflation is not like something we can directly measure. It's this diffuse effect on all these prices.

So we have this basket of goods to try to figure out what the inflation is for you as a person. But it turns out that is not the inflation for someone who's building a power plant. Because they don't care about the price of eggs. They care about the price of concrete. And other market forces are shaping the price of concrete. So there's actually different inflation levels for each activity.

And so the producer price index is an attempt to measure the inflation to make goods, if you will. It's the cost of labor, and machinery, and basic inputs, steel, things like that. It's another basket of goods. And, in fact, there's tables of producer price indices for all kinds of specific economic activities. And you can go look them up. Unfortunately, there is no index for building power plants, not one that is maintained by the Bureau of Labor statistics or anything for our benefit.

Sometimes you don't have a good index, either because none of these really fit, which is actually really the case for nuclear. Or you're working in another country. And when you're doing that, they may not have statistical agencies that track all of these index baskets. So one thing you can use is called the GDP inflator.

It's slightly different than GDP index, is just to say what is the growth rate of GDP index to some year. So they set a certain year to 100. And so don't get confused with the GDP index. But the GDP inflator is a measure of the growth rate of the GDP as a way to try to understand what's going on with inflation.

So the basic lesson is if you're going backwards looking in time, you have real data. You can use real data to do your guesses. If you're going forward in time, you don't have real data, because you're dealing with the future. So just you just forecast it using some historically average number.

So generally, we say about 2% to 3% per year under ideal conditions. But it's actually a little bit higher now. And it's been higher for a while. And especially for producer stuff. Cost of steel, cost of concrete has really been going up in recent years, cost of wood especially. So you look around and come up with a number and you just forecast.

All right. What about the interest rate on the loan? Well you could look up historical capital bond return rates and things like that to try to measure the capital markets. Generally, if you don't know the quick back-of-the-envelope calculation is you take the 30-year Treasury bond rate, which is the so-called risk-free rate. This is the rate at which essentially it's not-- the 30-year is not exactly the same. But it's basically the rate at which banks borrow money from the federal government, and then add 5% risk factor.

So this is kind of a quick back of the envelope. Historically, people called it about 10%. In this class, I'm going to argue that finance has actually gotten such that we can do it for about 8% right now. Typically, over the past 20 years, average cost of money to a utility company is about 7.7%. But money's gotten a little bit more expensive. Borrowing money has gotten a little bit more expensive. So let's say 8% right now.

Bottom line, you don't need to-- I'll put these again on the slide. It's a little bit tricky sometimes if you're combining rates and combining periodic rates, you can't just add them. So as things are compounded, let's say monthly, we can't just add them together. You have to use this equation. If you're using a force of interest or just continuous compounding, you can just add them together. So just you may not remember this. OK.

All right. So I already talked about loans. I mentioned that they are in nominal dollars, that the inflation rate is baked in. And just don't forget to watch your signs, to make sure that everything is going in the right direction.

So earlier, we had a question about deflation. And I just want to address that a little bit more. So here is the United States' inflation rate going back-- I don't know. This is 1950. So this is probably 1930, is probably the Great Depression, huge inflation then deflation. We've had periods where 15%, 20% inflation. That means the next year your money is worth 15% or 20% less than it is today, a really bad situation.

And we've gotten better at doing economic policy or monetary policy in this country and gotten ourselves to basically this period of stability where it was in this 2% to 5% region here. We saw a lot of inflation right after COVID. And we're trying to bring that back down. Hopefully, we can do that.

But just to give you a sense of the situation in the US, here's the situation in Iran. Look at these numbers. The low is 4.9. It goes all the way up to 49%, highly variable even in recent years. What's going on here? Part of it is they're not as good at monetary policy.

But a lot of this stuff is driven by over-dependence on oil prices as a source of income for the country. So there's big shifts in the availability of money, as well as things like sanctions, and other kinds of economic pressures that limit the ability of Iran to engage in trade. And so they have these wild swings.

So here's the problem. You want to build a nuclear power plant in Iran, and you're going to borrow $1 billion. And then like the next year, that money is worth basically half of what it was. What are you going to go? What is the loan going to look like? What's the interest rate on that loan going to be? Is it going to be 45%? You can't possibly pay back a 45% loan, right? So how do they get around this?

One of the things they do is for major civil projects, they try to have these countries who have unstable economies try to basically trade in dollars. They try to buy power plants in dollars as much as possible. It's the case that not everything can be done that way, because ultimately there are local workers, and local concrete companies, and so on that have to operate. So there is some exposure.

But to the greatest extent possible, what they try to do is they try to stabilize pricing by taking loans in dollars, paying them back in dollars, buying things from other countries in dollars. And this is why the dollar is the universal currency, and this is why people worry about things that would destabilize the dollar, like having way too much debt that we can no longer service and make our payments on, which would cause us to default on US Treasury bonds, which would then cause the trustworthiness of the dollar to go down.

So this is just giving you a picture, a global macroeconomic picture, about why stable currencies are important and also important to getting things done, like building nuclear power plants. OK, so this is high school or elementary school. You all remember that equation for calculating the effect of compounded interest, where n is the number of periods and the interest rate is specified as per period.

And then we learned about continuous compounding. And if you can't remember this just, remember "Pert." principal times approximate rate. Technically, it's the integral of the rate over time and you integrate over it. But if we're doing forecasting it will be just a fixed rate. And this has a special term. This r is distinct from this R. This is the interest rate. This is the so-called force of interest, though everyone just calls it the interest rate. So that's the [INAUDIBLE].

So again, I'll put these up on the slide. This is just to remind you that when you're doing some calculations, you have to be sometimes a little careful on how you find equivalent rates. So if someone gives you a loan, let's say, certain amount compounded monthly, and you want to know the effective annual rate, you have to solve the equation. You say, OK, it's a 5% monthly rate of 12 months is equal to what rate for one year, and solve this equation to get the answer. You can't just divide numbers.

That vibrating screen drives me nuts. All right. I think that's good enough.

OK, so the other thing we have to do, so that is just a rapid reminder about the interest rates and where they come from and what is really going on behind them. The other thing that we're going to need to have at the tip of our fingers are solutions to these infinite series. So how can I do this? I didn't bring a laser.

The top line is for a single period to convert from a future value to a current value, or vice versa. But then sometimes we'll have these situations where we'll have a lot of payments being made, and we want to know what the value is at the end. Or we spend a certain amount of money, and then we need to know how much money we have to get back on a certain periodic basis to pay off that loan. And so there's a continuous compounding equation. And there's a periodic compounding equation for all of these things. And then there's some fancy ones here.

These come in useful, surprisingly, if you work on predicting the value. If you're doing any kind of calculation about the value of some kind of power plant or so on, you'll probably wind up wanting to have these equations somewhere. So just stash these away in your files in case you need them. We'll use them a little bit later today.

OK. So any questions on interest rates? Blah, blah, blah, all that early stuff? OK, good. So now, we want to calculate using this quick review. We want to calculate the cost of electricity from different kinds of power plants, nuclear plants and non-nuclear plants, to see how they stack up.

And it turns out that it can be surprisingly difficult to get this number right, especially if you are forecasting. It's easy to get it right if you're looking at historical data, well, kind of easy to get it right. But if you're looking forward, it's easy to make mistakes. So let me just show you this plot.

This is from the Nuclear Energy Institute. Who can tell me who NEI is? OK?

AUDIENCE: Pro-nuclear, quasi like [INAUDIBLE] group, in parallel of Greenpeace, that's like super pro nuclear.

PROFESSOR: Yeah, they're an industry advocacy. They're a nonprofit industry advocacy that goes to Congress and says please make bills that are favorable towards nuclear. Every industry has such a lobbying organization. So when you see data from NEI, you immediately go, OK, this is the lobbying, pro-nuclear lobbying. So we have a grain of salt. And here they have the US electricity production cost, and they have oil and gas, and they have coal here in yellow. And then they have nuclear here in red. And it's the cheapest form of electricity. Is this plot correct? Yeah?

AUDIENCE: It's measuring production cost.

PROFESSOR: Ah, what is the production cost?

AUDIENCE: So in the case of coal, gas, no, gas and oil, it's the fuel that's used.

PROFESSOR: Yeah.

AUDIENCE: And the fuel, the price can be volatile.

PROFESSOR: Well yeah, and that's especially why the gas price goes up and down a lot. Yeah. Yeah. So this is the marginal cost of making the next unit of electricity and ignores all the cost of building the power plant. That's what this is. And so there are many, many things that you have to pay for. And the fuel is only one of them. And they have these different categories, which I will mention [INAUDIBLE]-- capital, a variable O&M, fixed O&M, and so on.

So all of these things in principle have to be rolled in. But basically what we do is for the purposes of modeling, we can take all of these and we can lump them up into a few categories depending on how they behave. And so here's our lumped model. We have capital cost, fixed O&M, and variable. Usually these are specified per unit of energy-generating capacity.

So a kilowatt of capacity, whether or not you actually generate a kilowatt of electricity or not, you're buying capacity. And then this is also fixed O&M, is what is fixed O&M? This is paying your employees to come to work, paying health-care costs. These are ongoing costs involved with running the plant that you can't just not pay, insurance for example. And this will typically also be priced per kilowatt of capacity.

And then we have variable costs, which are per-unit energy produced. So this would be per kilowatt, per kilowatt, per kilowatt hour. And typically these are fuel cost and some maintenance costs. Some maintenance costs go here. Some maintenance costs go here. And the key thing is that they give us this line equation, the total cost of producing q units of electricity is the variable times the amount of electricity we make, plus these fixed costs-- capital, fixed capital charge, and fixed O&M costs.

And so what we have is actually a family of lines for all the technologies. And we will draw that family of lines and explore how they interact maybe by the end of class today, maybe next class. But the first thing we need to do is get this number right, the capital cost.

All right, so let's do this. Let's see. All right. So you want to find some data-- OK. We'll do the calculation in a moment. But mostly you want to look up these data. So where do you look it up? So in the United States, the best place to look up this data is the Energy Information Administration. EIA is a statistical agency.

We have a lot of statistical agencies like the Census, and the Bureau of Labor Statistics, and so on. So they employ hundreds of statisticians. About 300 people work at EIA, although Doge laid off about 100 of them. And their job is to figure out the true cost of building power plants in the United States.

And in fact, they are authorized under law, under the Federal Energy Administration act of 1974, to send surveys to utilities, and those utility companies are required under law to complete these surveys, called form 860 and form 903, reporting on how much money they spend on maintaining their power plants and building new power plants. And then the EIA also looks at other sources of information, like annual reports of different utility companies. And it aggregates all this data to get you good statistics on actually what's going on, and use that to make policy.

And so EIA is phenomenal. It really is the best source of data. Generally, there are a couple of other sources that you can use. Lazard is a private company that has made a business of trying to generate these statistics. And then if you're working in other countries, there may be other government accounting and audit offices. For example, in France, it's the Court of [NON-ENGLISH]. I don't actually know what it stands for. Does anyone know?

There's basically a court.

AUDIENCE: It's a court of auditors.

PROFESSOR: Maybe it's the court of auditor. I thought it was CRMTES. Yes, but there's a court that basically issues these statements and they have a very unusual methodology. So if you use their data, you have to understand their methodology. There are others, like India has public auditing offices that publishes stuff online for power plants and so on. So those are useful.

And then if you can't use those, you can look at annual reports and utility reports, SEC filings, to try to approximate things. So if you're working on setting uranium enrichment, EIA does not collect data on the cost of building enrichment plants. And so you have to back it out from corporate financial reports and things like that.

So let me just show you what EIA actually publishes. I don't know if you can read this. I hope you can. Yes? OK. So let's just quickly walk through it. This is just saying, they're assuming that this technology will be built on a certain year, that is to say, because the cost changes slowly over time, reduce their index of when this thing is actually getting built.

This is the size, obviously the cost is dependent on the size. If I build a tiny little power plant that makes 1 kilowatt, 1 kilowatt of electricity, like my little backup generator, it's going to have different capital dynamics than if I build one that produces a megawatt, right? So you have a reference size. Is that pretty typical though? And for the most part, these things are set. This is the sweet spot where the vendors have figured out this is where the economics works out well.

So these are generally you don't generally have to worry about these too much, but you might have to a little bit. So for example here in nuclear they're saying 2,000 megawatts. So they're assuming you're building two full-size 1 gigawatt plants together. That's what that means. If you're building just one, the price is not the same. But typically, almost every one in the world now builds two at a time.

Small modular reactor is another place where you're going to see some dependence on the number. They're assuming a 600-megawatt small modular reactor installation, which is usually a whole bunch of smaller modules, like maybe 12 modules to get you up to 600 megawatts.

Then they have the lead time, how long it takes to build. These data are also collected by the EIA, and for the most part, they're correct. But we'll talk about where they might not be correct in a moment. Then they have the baseline capital cost, and this is new this year, the technological optimism factor, and then the total overnight cost. So what is going on with this thing here?

So basically, they're saying where we have good data, we don't need to have any kind of forecast error. Because we've built lots and lots and lots of natural gas plants. And we know exactly what they put, what they will cost. And so when we look at our data, we know what they cost. And so the technological optimism factor for these combined cycles, which are all natural gas is 1, except if it has carbon capture and storage, because we don't build a lot of those. And so there's a little 2% increase because we really don't know what the cost is for carbon capture and storage.

Offshore wind is another technology we haven't really built. And so they've assigned it a 25% cost optimism factor, and so on and so forth. So where that has a unit of 1, you can basically say these numbers are statistically guaranteed. Yeah?

AUDIENCE: So like this for offshore wind, they're expecting costs could be 25% higher or what is that?

PROFESSOR: Yeah, so what they're saying is like the wind people are estimating this, and they're saying, well, we think they're low, and we're going to just arbitrarily plus it up by 25%. That's what they're doing. Yeah.

AUDIENCE: One more.

PROFESSOR: Yep?

AUDIENCE: So for the base overnight cost, footnote E says it includes project contingency costs. What are those?

PROFESSOR: We're going to build this power plant in six years. And then they're like, oh, but then it turns out that our environmental impact statement didn't get approved. And now there's a delay. And so they try to take the average contingency into account based on historical projects. Yep?

AUDIENCE: So are all the numbers on the table accounting for that technological optimism factor already, or is it for that [INAUDIBLE]?

PROFESSOR: So the one that says total overnight is accounting for the technological optimism. They don't have any discussion about whether the lead time should also be modified for technological optimism. They just give us this lead time. This is a brand new number. And I think they've only applied it to this column as far as I can tell. Unfortunately, they used to put out a lot of description about how these things are generated.

But under the new administration and since they've lost about a third of their employees, stuff is happening and reports are not being issued, and things are very information poor all of a sudden. So it's hard to figure out exactly what is going on with this.

AUDIENCE: Not to express strong skepticism, but aren't these numbers very arbitrary? I mean, especially for nuclear, most projects significantly underestimate both the overnight cost and the lead time.

PROFESSOR: Yeah, so for the rest of the class we'll be about talking about that. For non-nuclear, non-nuclear, non-CCS, not offshore wind, these numbers are really good. These numbers are totally solid. But anywhere where the technological optimism factor is not unity, there's fudge. And we'll look at how big that is.

AUDIENCE: What actually is the overnight cost?

PROFESSOR: Oh, thank you. The overnight cost is the cost of building the hardware, the power plant, ignoring all the finance charges associated with borrowing the money. So where it gets its name is to say that we're going to build this power plant overnight. And so the interest payment will be almost 0 because we can pay the bank back the next day. That's what the overnight cost is.

So it's a way of measuring the cost of the technology, independent of the finance environment. Because interest rates go up, interest rates go down, blah, blah, blah, blah, blah. If we track the true cost, then these numbers would not be predictable. So we take all that out and we just look at basically the cost of building this stuff. All right?

And then they also published the variable O&M, which is essentially fuel cost and variable maintenance cost, and the fixed O&M which is paying for your employee, paying your insurance. And then they produced this number called the heat rate, which is in BTUs per kilowatt hour, units of energy per unit of energy. Basically, this is just a measure of efficiency. But this is useful if you want to figure out the amount of carbon coming out of something. So you want to know the carbon intensity? You look up how much carbon is emitted per BTU of the fuel. And this number tells you how to convert that BTU into kilowatts.

So it allows you to calculate the carbon intensity of the power plant. We're not going to use that right away. All right, I think I have little bars to highlight those things. But oh, my gosh. We don't need to do that.

OK, so what is the overnight cost of nuclear? That's what we really care. Light water reactor, they say 7,000. They say with this little risk factor, they say 7,777. And why is this not 1? Because we haven't built a lot of nuclear plants in the United States. In the last 40 years, we've had one new build project with two reactors in the last about 45 years. We've completed a third reactor. That third reactor was actually started in the '70s, and took 45 years to complete.

So putting the capital cost of that reactor in there is just not a good idea. Yeah?

AUDIENCE: Is there any data for Naval nuclear reactors? Because we've been building those a lot more consistently.

PROFESSOR: That would be wonderful if there were real data for that. If anyone is a Naval ROTC person and can find that-- yeah?

AUDIENCE: Some data by the Congressional.

AUDIENCE: Yeah, there is some from the admiralty about it.

PROFESSOR: Yeah?

AUDIENCE: And the Congressional--

AUDIENCE: $1 billion for reactor development cost, $1 billion for the shipyard, and then they have some estimates. At some point, the Navy was apparently looking at, are we going to make our new ships nuclear or not. They did some very high level. So there is some data on it from Congress, but obviously, not too much.

PROFESSOR: Is there any time series data?

AUDIENCE: I don't think it has time series. I can try to pull it up. It's pretty old. I think it's from 2011.

PROFESSOR: Yeah. The only time series data, so this is of interest for learning, which we'll have a separate class about. Learning is how do we bring this number down. And the Naval reactors is a place where we build the same reactor design over and over and over. And we might see some learning. And so I'm very interested in time series associated with this. There is one Russian/Soviet number on time series for Naval reactors. And it's just this guy who publishes with no data. He just asserts that the cost reduction rate was 5%.

And very traditional, if you go back and read like Soviet era scientific publications. They don't put that data in there. It's all based on the reputation of the scientists that has put his name on the paper. And then you just take it as faith. So there's one data for time series and data point for Russian data. But I would love to see some data for the US reactors, if we could get it. So that would be super cool.

OK, so let's just look at the range of estimates that we see for this number from nuclear. All right. So this is overnight costs. Everything is in real 2023 dollars per kilowatt. So everything is normalized normalize to the reactor size. And this is the range of estimates.

All right. That's a lot of range. That's a factor of 11 between the top and the bottom. And just to make matters worse the top estimate and the bottom estimate are for the same reactor. In fact, all of these are estimates except for this one, which is actually the true cost of building Vogtle in the United States.

And so there's a few trends that we can observe here. The first is that the companies selling the reactors-- Westinghouse, Oklo, TerraPower, they always have the lowest estimates. Surprise, surprise. They need to sell this thing. They don't have to do the architectural engineering. That's done destined by an independent firm. They just design the reactor. Someone else figures out how to build it, and they come up with this number, and it's pulled out of thin air. It's not surprising that it's totally low.

Then you have these academics, mostly MIT, publishing these reports, estimating what? And so there, the academics are optimists. They're like, we like nuclear. We think that there are ways to bring down the cost. And so they publish these numbers, which historically, my department, our department started at $2,000 in 2002. That 3570 in 2023 dollars. We no longer are that optimistic. We're slowly becoming more pessimistic, but we're still more optimistic than the government.

And then the government, they hire now, they hired this independent contractor called Sargent & Lundy to do the cost estimation for them. It wasn't always the case. Sargent & Lundy has published these numbers. Now does Sargent & Lundy know what they're talking about. Yeah, they do, because they are one of the biggest architectural engineering firms in the United States. What do they do? You want to build a power plant? You go to the Westinghouse, you go to General Electric, you buy their technology. Sargent & Lundy figures out where the pipes go, how to pour the concrete, how this plugs into the grid. They build the plant.

They are the people who actually do what's called architectural engineering. So they really have some good basis, but they also sell architectural engineering services. So they are slightly conflicted in trying to come up with solid numbers. They want these numbers to be low, otherwise no one's going to buy their business.

And that's Vogtle, what it actually cost to build the plant. Yeah?

AUDIENCE: So one question on the overnight cost as the metric. Once constructed, the reactor will generate relatively cheap energy for a long period of time. So is there a different metric we can look at?

PROFESSOR: Absolutely. We're going to walk systematically through all of these things and get there. Yeah, this is not the measure of affordability. Let me just underscore this. This is not the measure of affordability of a nuclear plant, though it is a strongly important factor. But this is not the final measurement. Yeah?

AUDIENCE: For all of the AP1000 calculations, as it were, how many of them are for long term, this is the 30th AP1000 we've built. Because obviously the Westinghouse is that's n-th of a kind. But are the Sargent Lundy ones for n-th of a kind, as well? Because we would expect the first two as developmental units. And with Westinghouse's mismanagement over the AP1000 project, it's obviously going to be higher. But now that the technology is figured out, do we expect that to go down significantly or--

PROFESSOR: Yeah, so I think most of these are n-th of the kind predictions.

AUDIENCE: OK.

PROFESSOR: Does it say? Yeah, most of these are n-th of a kind predictions. Whether Vogtle is first of a kind or n-th of a kind, most people would say it's first of a kind because it's the first two built in the United States. But it's not the first two built.

AUDIENCE: There were two in China?

PROFESSOR: There were some. There were--

AUDIENCE: I know there were two built in China.

PROFESSOR: There are two built in China. Yeah. So it depends on how you look at this number. One of the issues is that every time you look at these actual numbers ex-post is all these some explanations for why this number is so big. And then it's up to you to believe whether that was a one-off or whether that's actually what it costs to build.

So this is where we are. Yep?

AUDIENCE: So this is a Westinghouse prediction for building any [INAUDIBLE]? Is there any availability to find Westinghouse's evaluation for building in other countries like South Korea?

PROFESSOR: I don't think I've seen that. No.

AUDIENCE: OK. I mean, I imagine, I just can't imagine they would estimate it even being even lower for those countries.

PROFESSOR: Yeah, I mean, this Westinghouse number goes back to 2002. It was early on. They probably thought the US was a principal market. And it's also the case that the AP1000 built in China has fewer safety features than the AP1000 built in the United States.

China was like, we're not going to pay for that. And so they made the containment thinner, uses less concrete, various things. Also, the design slightly changed between there and here because of 9/11. So they made the containment in the US plant thicker, so you could fly an airplane into it and it wouldn't have a puncture. Whereas in the original design, the containment had slightly less concrete. But that does not explain a factor of n and deviation.

So any other? Yeah? Yeah.

AUDIENCE: So I'm wondering how are they making these predictions, especially for n-th of a kind, when historically we don't actually know if positive learning is something that properly happens for nuclear? Like we haven't really seen that be a thing yet. So are these assuming positive learning?

PROFESSOR: They often assume a little bit of positive learning. Yes. And sometimes you can get first-of-a-kind numbers out of these guys. I don't know what went into that Westinghouse where I have to go look it up. But usually like learning rates are assumed to be 5% maybe 10%. So they would say a full-out number of 1,760 maybe it'd be 2,000. Yeah, that would be their number.

AUDIENCE: Why have MIT's estimates become more pessimistic over time?

PROFESSOR: Because the first ones were really just based on nothing. Yeah, so the first report was basically a propaganda report. And the second report, which was an attempt to genuinely understand why nuclear was so expensive, did identify a number of things that were changing. In particular, they looked at the productivity of labor, and they concluded that it had been going down over time. They concluded that actually, cost of steel, cost of concrete is going up. So there are real reasons to understand that the original predictions made by Westinghouse and others were probably not correct.

But they still picked reasonably optimistic numbers. And what they did for their median number was to actually not devise it themselves. But they used NREL, National Renewable Energy Laboratory, which devised a number. And then I forget. I looked this up. At one point, I think NREL got the number from a conversation with Westinghouse. It turns out that this number, this number changes every year.

But when I first started teaching this class, I really wanted to know where it came from. And this was before Sargent & Lundy did these tables for them. So I called the EIA office and I finally got in touch with the person responsible for the nuclear cost estimation. And I said, where do you get your number? She's like, oh, I call Westinghouse every year and add 10%. There you go.

So let us now look at how to calculate. Let's see, nope, wrong one. Let us look a little bit at what goes into the calculation of the capital charge. So what we've looked at is the overnight cost, which is not the capital charge. The overnight cost assumes that you're going to build the plant overnight. You never build a plant overnight, so you have some interest to pay on it. So let's just look at that really fast.

So typically when you build a plant, you're going to have some expenditure. It's typically going to be very small in the beginning because you're doing some studies. You're going to have some geotech engineer come out, drill holes. You're going to dig a big pit in the ground. And so your costs are low.

And then you're going to ramp up. You're going to start doing all kinds of construction. And then you're going to ramp down. And there's going to be some total construction time. We're call that big T. There are people who have tried to study the shape of this and fit functions based on historical cost data. And often what they fit is some combination of cosines and hyperbolic cosine. But basically it's a slightly flattened cosine shape or roughly a parabola shape. And it turns out, it doesn't really matter.

You just need some kind of convex down shape. And so I like to basically say that the intensity of spending is basically some general quadratic, like that. That will be some general quadratic that describes a parabola. And then we have three boundary conditions that the intensity at time 0 is 0. The intensity at time big T is 0, the two roots, and then this area under the curve, the integral of the intensity-- sorry, I'm being sloppy-- from 0 to big T should be the overnight cost. Right?

Our three boundary conditions allows us to solve for these three parameters, and we can determine the shape of this curve. And I will leave that as a problem for the reader, instead of wasting six minutes doing algebra for you. And if you do that, you're going to get this nice result, which is the intensity of time t is 6 times the overnight cost divided by big T cubed times t times big T minus t. That turns out to be the equation for a parabola that fits this shape.

So what is this thing doing? This is predicting this shape. And we have now to worry about interest. So we have some little amount of spending that occurs at some time, p star. And we need to consider inflation and we need to consider interest. So how much spending do we do there? It's I of t dt. How expensive is that?

Well, we started here when we were doing our calculation. But now this happens in the future. So there's going to be some inflation that's driving the price of the goods and services up that we're trying to buy. So we take I of t dt times the inflation rate times the amount of time that has elapsed. And that is how much we have to spend.

But then to buy it, we have to take a loan from the bank because they're not making any money, or borrow money through bond market or through some kind of mechanism of financing this. And we're going to have to pay interest on that loan for this period until we can begin making electricity. And this is big T minus t. So we have another here, which is I call it w which is w for the weighted average cost of capital. And it's like, OK, some interest rate for bonds, some interest rate for equity, some interest rate for all the different mechanisms which I finance this plant weighted over the fraction of each mechanism, it gives you w times big T minus t.

So that's our essentially cost in real dollars by the time we get to the end of the construction project for building that single unit. And then we're just going to integrate that from 0 to t. So we have 6 times the overnight cost over T cubed times t times big T minus t times e to rt e to the w T minus t. All right. And that is equal to what is called our investment cost.

This is how much we've got to-- totally, this is the amount of the loan by the time we get to the end of the construction period that we have to pay off after we build the plant. So why am I like walking you through this? Because I want to show you how important it is not to have delays during your construction. Before I move on to that, does anyone want to ask about anything here? Yes?

AUDIENCE: You said I was intensity. Can you explained what intensity is?

PROFESSOR: Yeah, it's the rate of spending. So it's the dollars per unit time as a function of time along your trajectory. Yep. Yeah?

AUDIENCE: So it's the second exponential with the w, so essentially your interest payments. Is the assumption, now that you pay back your loans by the end of construction, wouldn't you take out, I don't know, 20-, 30-year loans anyways.

PROFESSOR: We'll get to that in a moment. That's the amount that will be, if you could pay it back the moment you operate, that would be the balance, the balance due. Now you're going to actually pay it back over a longer period of time. But this is the balance due, if you will, on the day you begin operating. It is called the rate-based cost. It's the cost at which you would set your price of electricity. It's the cost that you would use to determine the price of electricity, that we could pay off the plant by the end of its lifetime. Any other questions?

OK. So there's the same equation. I don't think I need the board anymore, so let me put this down.

AUDIENCE: Sorry. I do have one question.

PROFESSOR: Yep?

AUDIENCE: How do we know that construction costs or intensity costs will peak somewhere in the middle of the construction? How do we know that?

PROFESSOR: Just historical experience, yeah, so it typically looks like that. Yeah, so if you have actual data for how much was spent, and you're doing a retrospective on a plant, then you would actually just generate a big spreadsheet and say, in this period, we spent this. And you would do it period by period, and it'd be whatever shape it is. But we're trying to forecast for different technologies. And generally, it has this shape and it doesn't matter all that much if the shape is exactly a parabola or part of a sine wave or something else. Yep?

AUDIENCE: So with the e to the wt, is that just assuming we're taking out loans as we go continually?

PROFESSOR: Yeah. And really it does work that way. You have bond offerings and you maybe do an offering every year or so. You don't want to borrow all the money upfront and pay it anyway. That would be stupid. And even if you did borrow the money upfront, what you would probably do is then invest it and get interest rate returns. So it's basically a wash.

AUDIENCE: Yeah.

PROFESSOR: Yep?

AUDIENCE: How might this change if you're an SMR company in more recent years and you're more funded by VCs rather than loans, like a lot of your frac?

PROFESSOR: It's the same. That was the same question earlier. Basically, yeah, so there's something called the debt-to-equity ratio. And so a lot of that will be equity-based financing. But the idea is that they are taking ownership shares, and they expect that there will be some return profit from the company, which you will then have to give them because they own part of the company. So it's all the same mechanism at the end of the day. What's changing is really the legal structure of how you get paid.

But fundamentally, there's still some return that is being promised. Yeah. Anyone? OK.

All right, so what you see here is that the time, I've basically solved this equation. And I didn't put the solved equation up there. Do I have it somewhere? Well, if you do the integral, you can basically get an expression for IC times a constant, assuming some values for rw, times ON, the overnight cost. Does that make sense?

So the investment cost is some multiplier times the overnight cost. And I just want to show you what happens as the construction time goes up. Interest rates are fixed, cost of money is fixed. But as the construction time goes up here's what happens to your investment cost.

It starts out, it's at 1.1, 1.2, 1.3 and then 2, and 3 times more than your investment costs. So if you have big delays, this is a problem. So the EIA was saying six years to build the nuclear plant. And it would only cost 40% more than the overnight costs. But in fact, Vogtle took 14 years. And so it's 2.3 times. Flamanville and Olkiluoto cost one was 17 and 1/2, the other was 18. So they cost about 18-- and they cost about 3 times the overnight cost.

So building your plant fast is really important. And this is why people love the idea of factory fabrication. And so now we've motivated this idea, stick building nuclear plants, if it's a very slow and drawn out process, it's going to be very expensive. If we can get away from that, you can do factory fabrication, that's much better.

Let's see. Where are we? We have just a couple minutes. Let me leave it here and just say that I've done the math for you. Assuming that this number is correct for the construction time, and now you can see what the investment cost would be for different technologies. And you can see some trends starting to emerge. You can see that solar thermal is not very interesting. We don't see a lot of solar thermal plants being built.

You see that nuclear is still expensive, bit remember, this is only the capital charge. We have not done the full cost yet because we haven't done fixed O&M. We haven't done variable. And some of these might have components particularly significant.

What else is interesting here? Carving a hole is actually fairly expensive, which is why you don't see a lot of coal plants being built in the US. Fuel cells are super expensive. So you can see there is a reason why solar with tracking or solar with tracking and batteries is being built so crazily. It's just a lot cheaper to build. This is a Vogtle here at the bottom, in case you want the actual number for Vogtle.

All right. So when we come back, we will do the rest of these and figure out the true cost.